Dispersion curves of overtones extracted from seismic ambient noise data and corresponding inversions

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Acknowledgement to Collaborators：

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- University of Science and Technology of China:
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- Southern University of Science and Technology:
  Zhen-tao YANG, Gong-heng ZHANG, Li-na GAO

Motivations

- Seismic Surface Wave Tomography (SSWT) is an important method for inverting the Earth interior structure
- Ambient Seismic Noise Tomography (ASNT) greatly extends SSWT frequency band, with much rich data, especially short period data.
- However, both methods are facing the problem of *non-uniqueness* in making the inversion.
- Solution to such non-uniqueness problem is find more independent information, increase constrain
- Currently, both methods use fundamental mode information only
- However, the data contains more information, e.g., the overtones, if we can find and use them, the non-uniqueness problem can be overcome.

Outlines

- Importance of higher modes for SWTM, as well as ambient seismic noise tomography
- How to extract the dispersion curves of higher mode from ambient seismic noise?
- How do the higher modes improve the inversion?
- Brief introduction of F-J method

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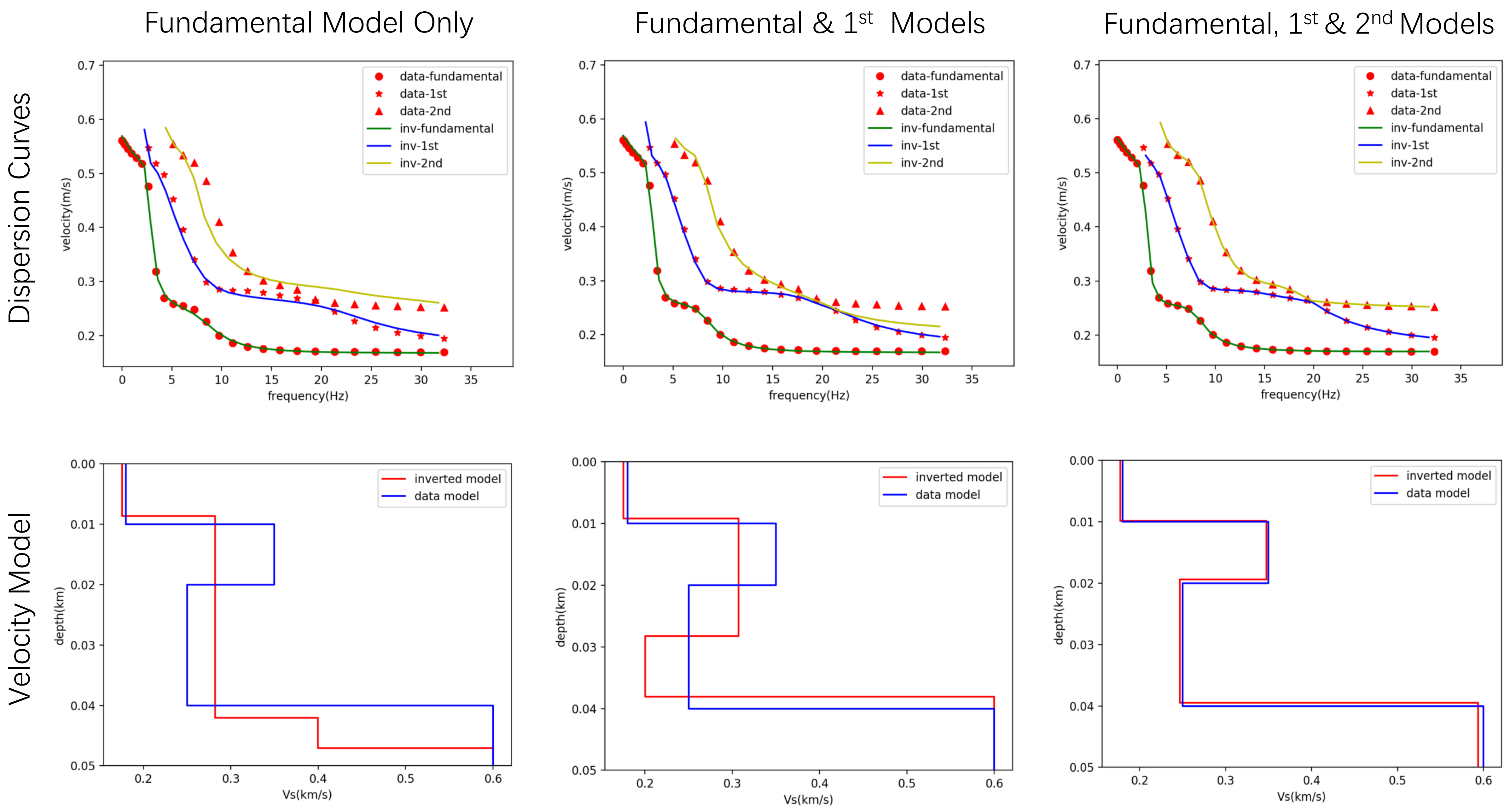

Fundamental Model Only
Fundamental & 1st Models
Fundamental, 1st & 2nd Models
Dispersion Curves
Velocity Model
velocity(m/s)
frequency(Hz)
data-fundamental
data-1st
data-2nd
inv-fundamental
inv-1st
inv-2nd
depth(km)
Vs(km/s)
inverted model
data model

We propose a new method for extracting dispersion curves of higher-modes:

Frequency-Bessel Transformation Method

(F-J method)

ADVANCING EARTH AND SPACE SCIENCE

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2018JB016595

Key Points:
- We proposed a new method (the F-J method) to image dispersion curves of overtones of Rayleigh waves from ambient seismic noise data
- Preliminary applications to USArray

Frequency-Bessel Transform Method for Effective Imaging of Higher-Mode Rayleigh Dispersion Curves From Ambient Seismic Noise Data

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Wang, J., Wu, G., & Chen, X. (2019). Frequency-Bessel transform method for effective imaging of higher-mode Rayleigh dispersion curves from ambient seismic noise data. *Journal of Geophysical Research: Solid Earth*, *124*. https://doi.org/10.1029/2018JB016595

ambient seismic noise data. *Journal of Geophysical Research: Solid Earth*, *124*. https://doi.org/10.1029/2018JB016595

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1. Introduction

Ambient seismic noise, which is also called microtremor in the field of geotechnique engineering, is a stochastic wavefield generated by various passive sources (e.g., Okada & Suto, 2003; Yang et al., 2007; Yang & Ritzwoller, 2008). After the pioneering works of Aki (1957) and other researchers (e.g., Campillo & Paul, 2003; Derode et al., 2003; Lobkis & Weaver, 2001; Sabra et al., 2005a, 2005b; Sánchez-Sesma et al., 2011; Shapiro & Campillo, 2004; Shapiro et al., 2005; Snieder, 2004), once useless ambient noise data were con-

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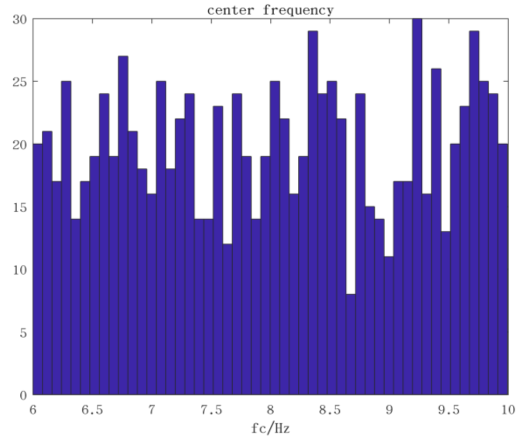
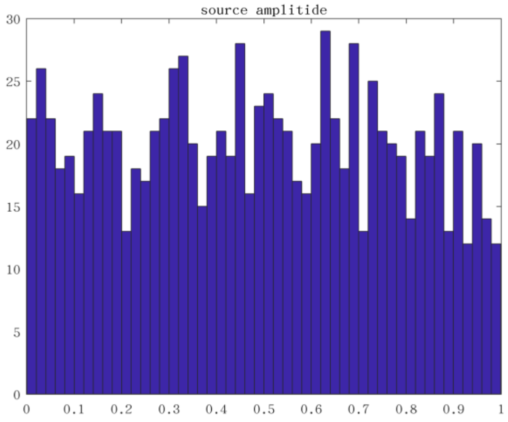
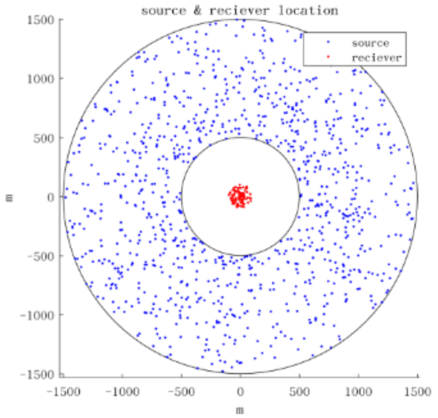
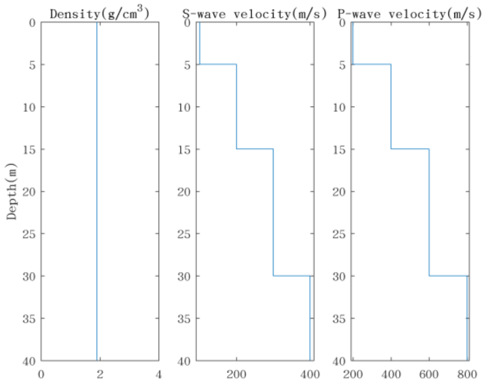
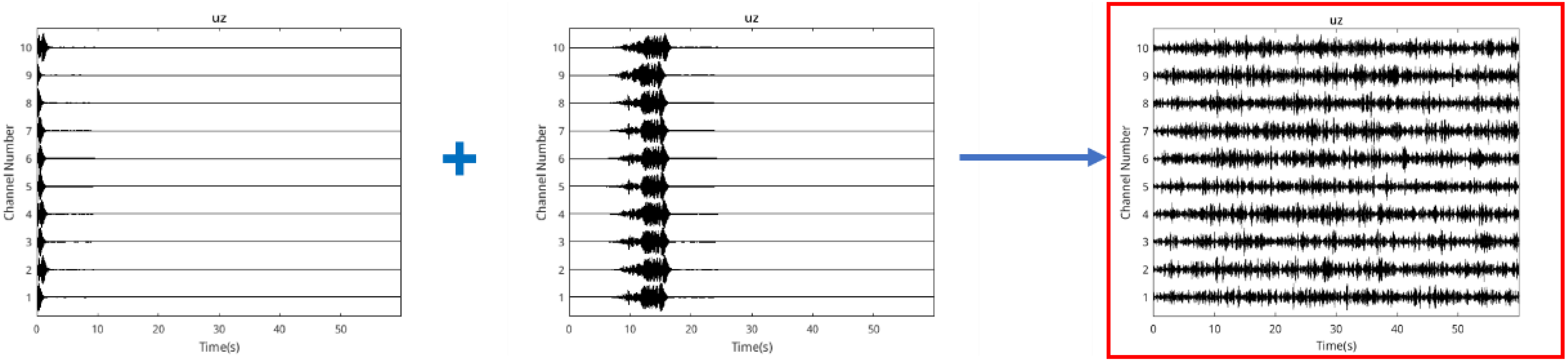
Synthetic seismic noise：



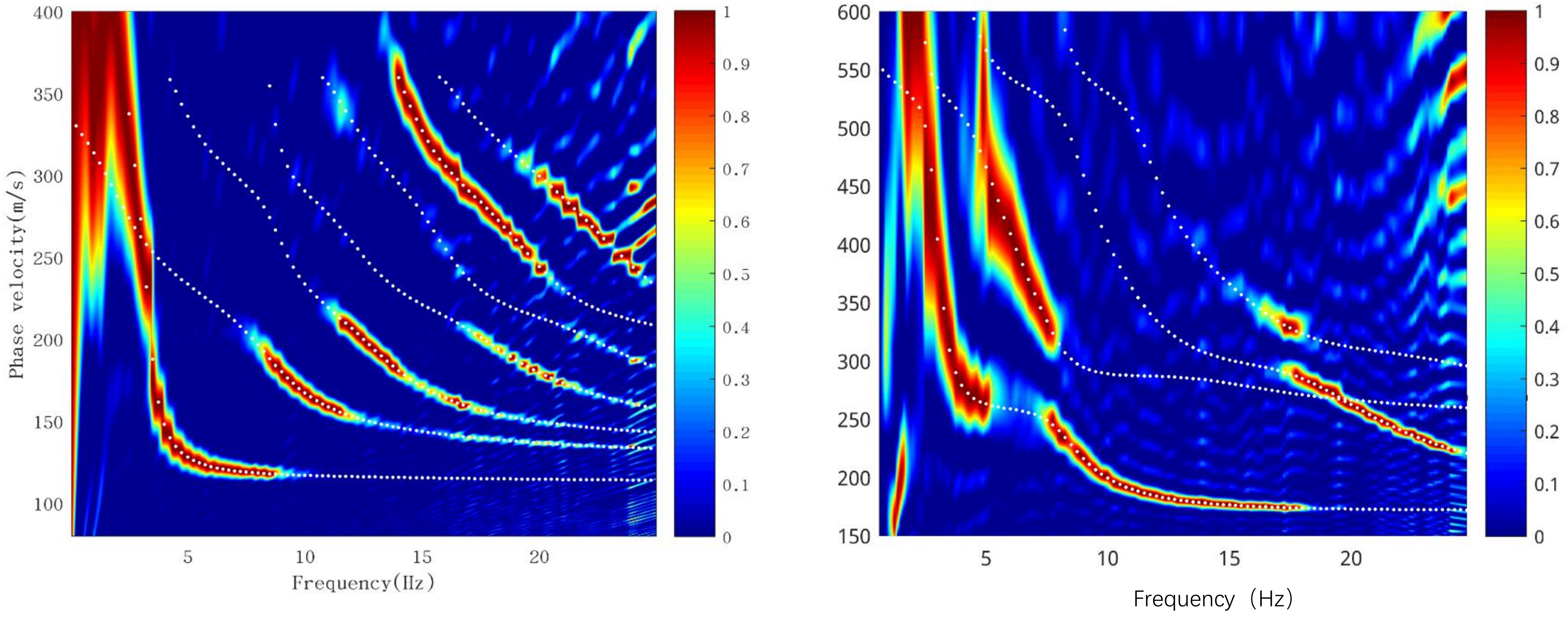








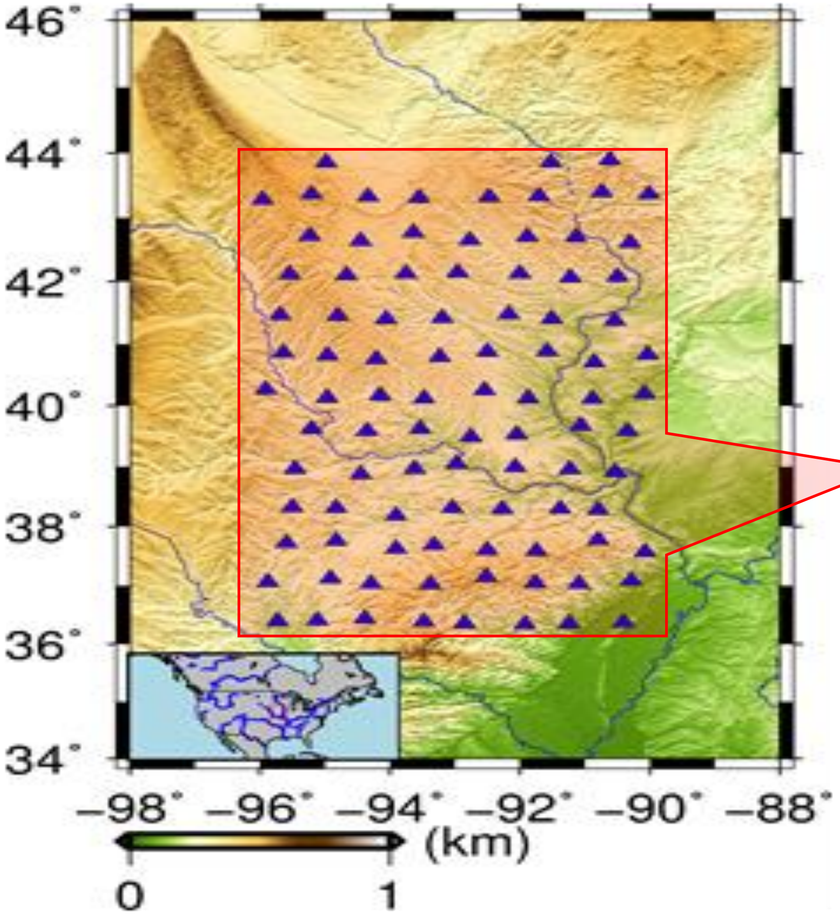
Using F-J method to the synthetic data:

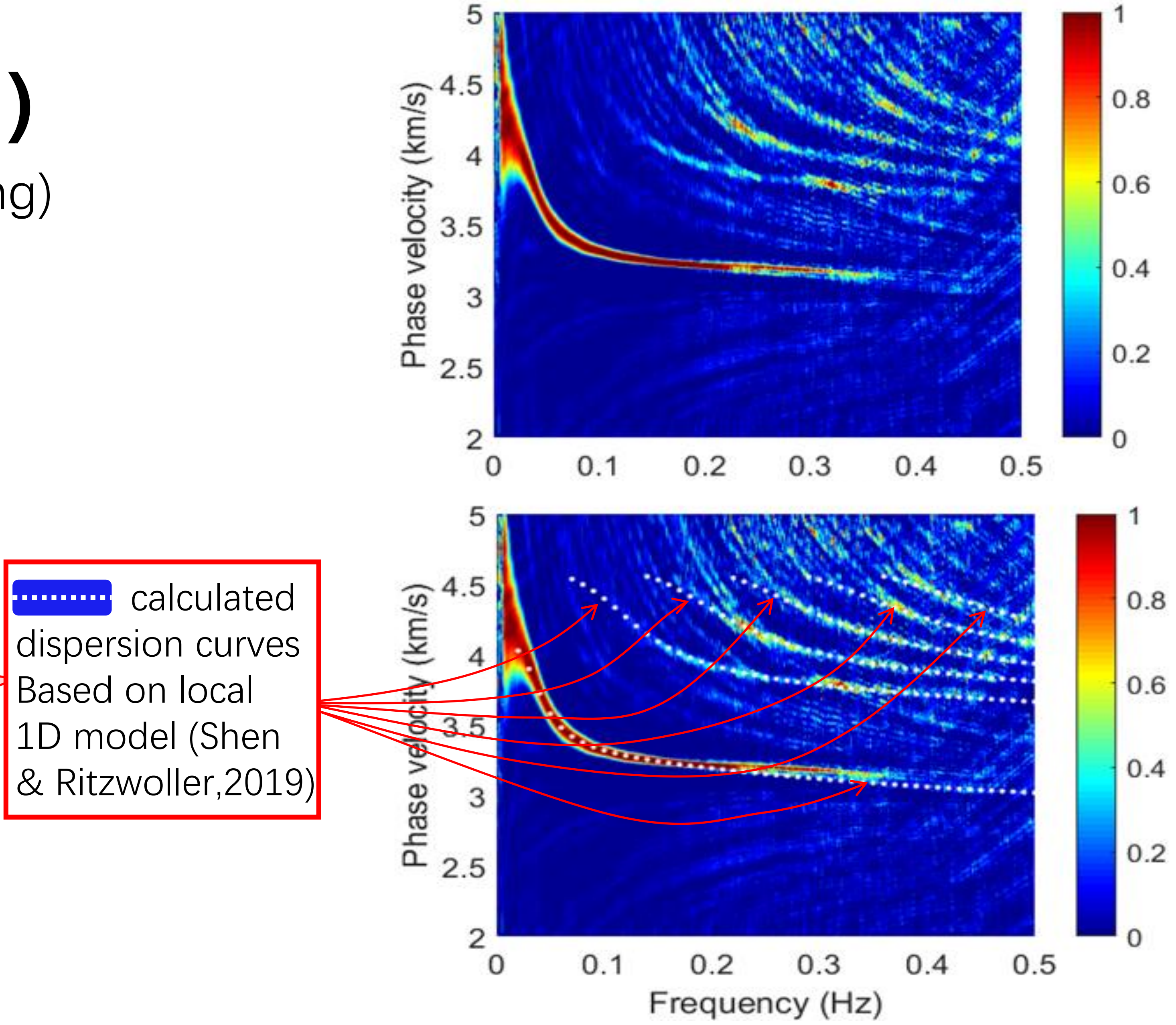


Results from USArray ambient noise data (1)

(96 stations, 6 months recording)

Central US

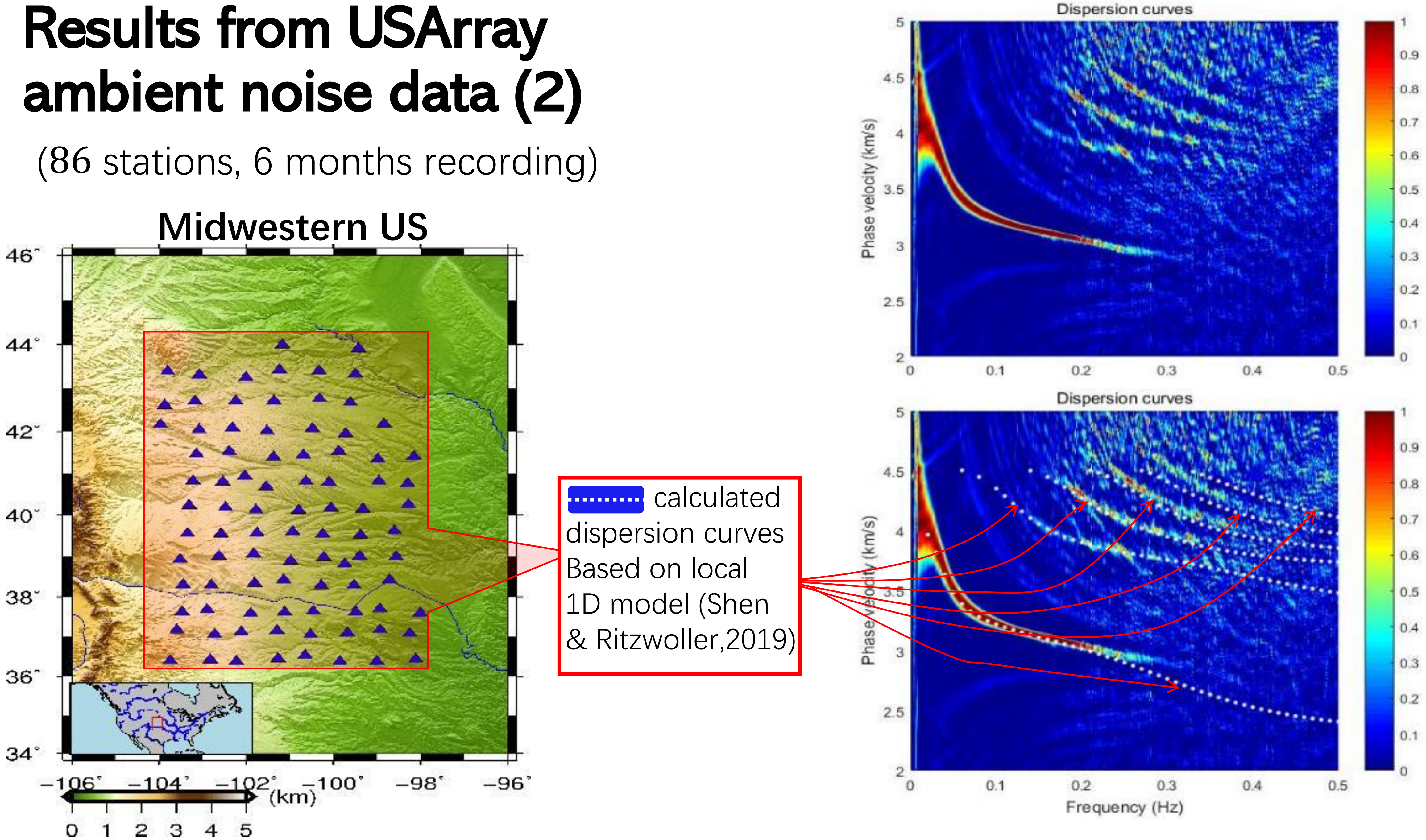




Results from USArray ambient noise data (2)

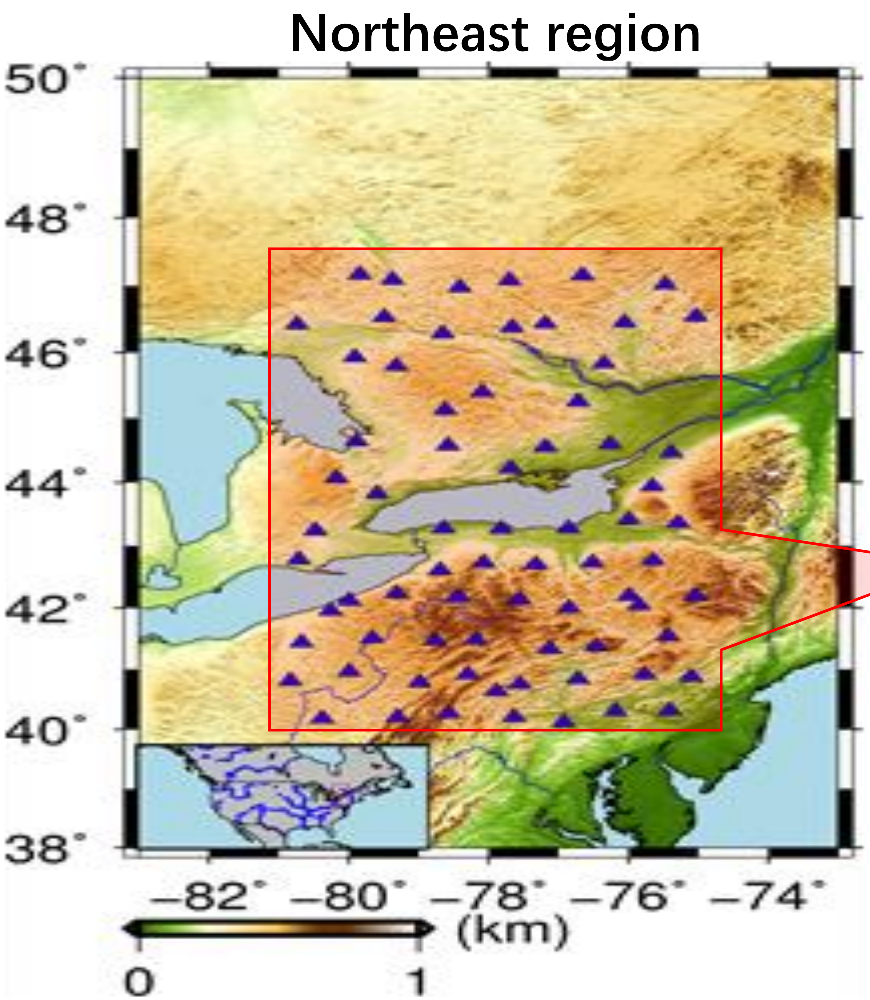
(86 stations, 6 months recording)

Midwestern US

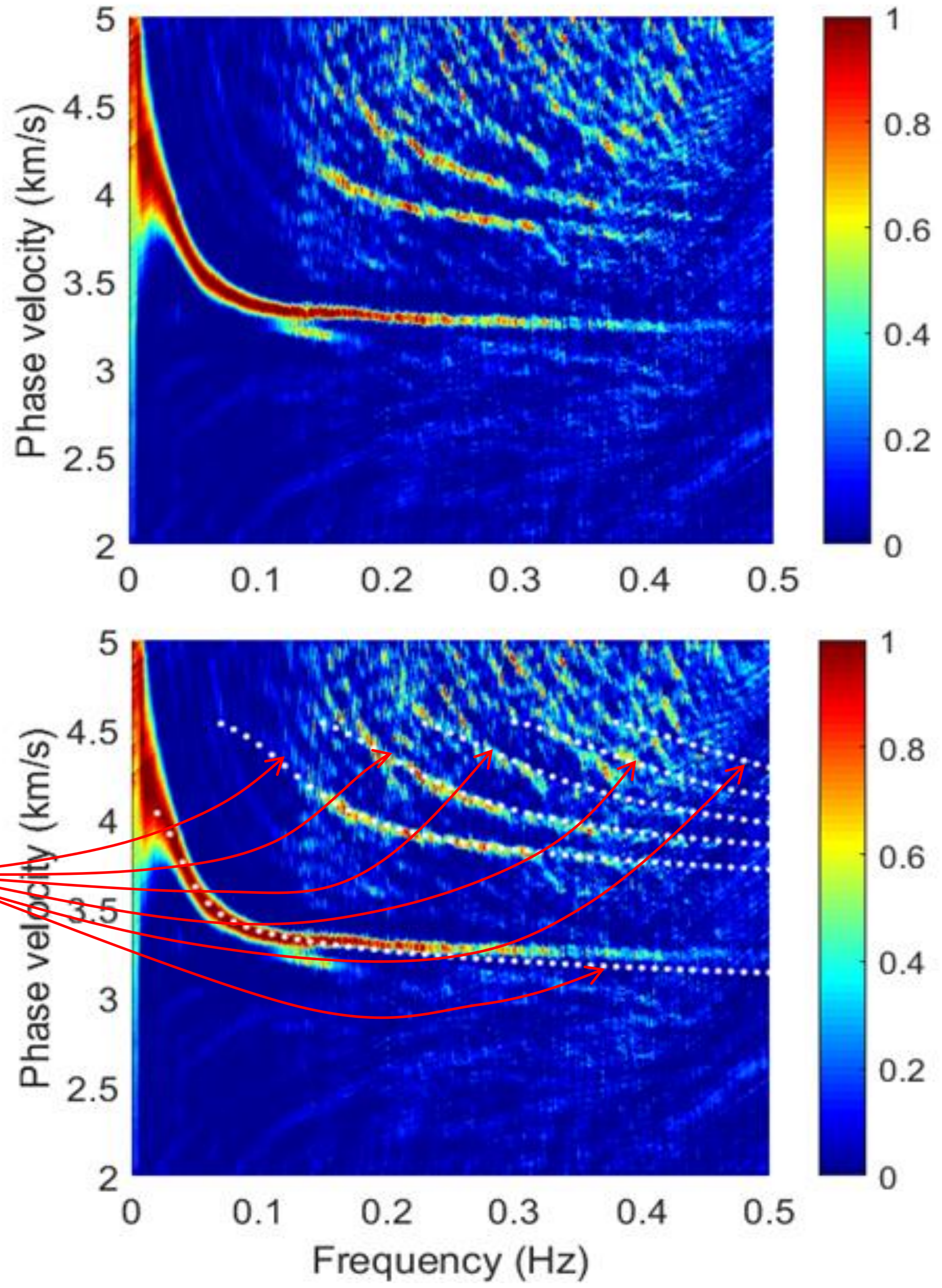


Results from USArray ambient noise data (3)

(73 stations, 6 months recording)



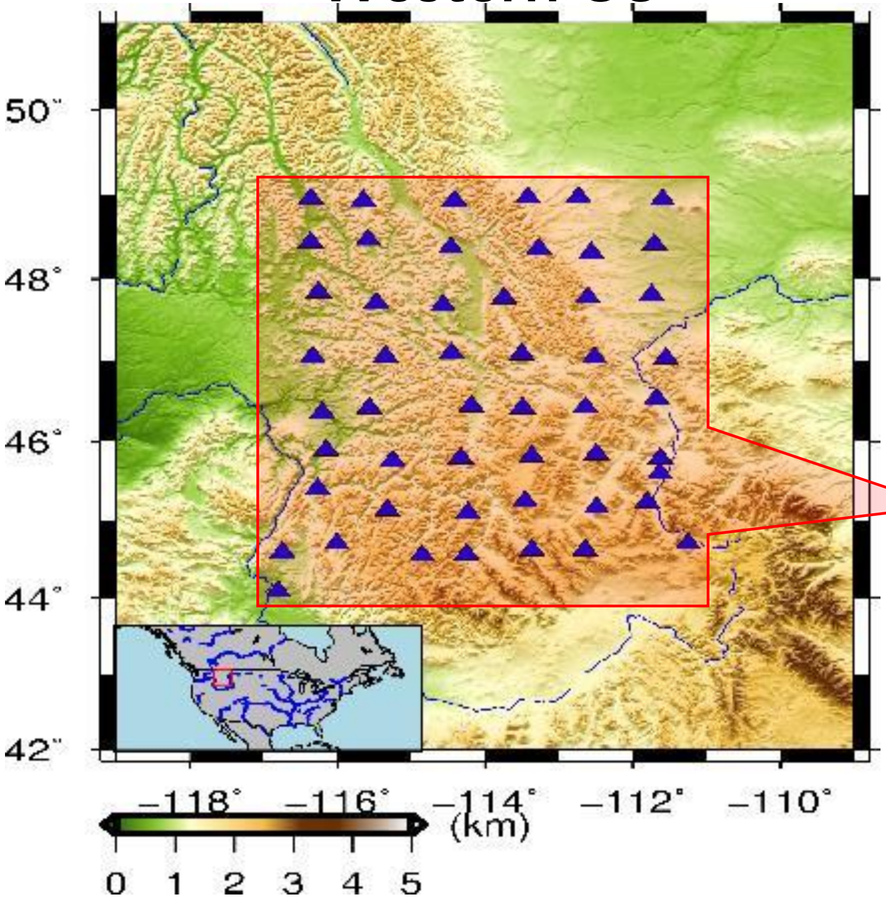
calculated dispersion curves Based on local 1D model (Shen & Ritzwoller,2019)



Results from USArray ambient noise data (4)

(51 stations, 6 months recording)

Western US



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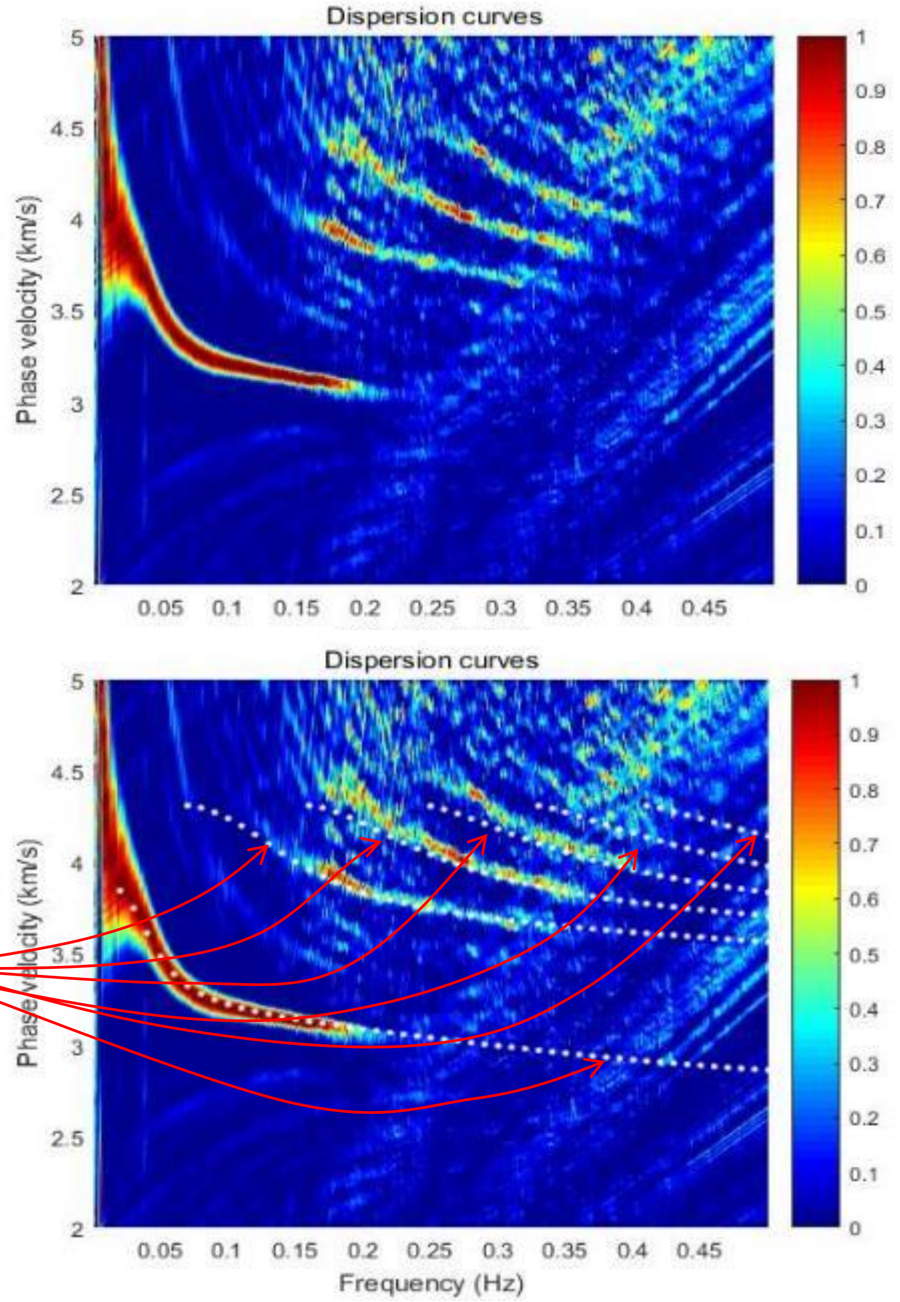
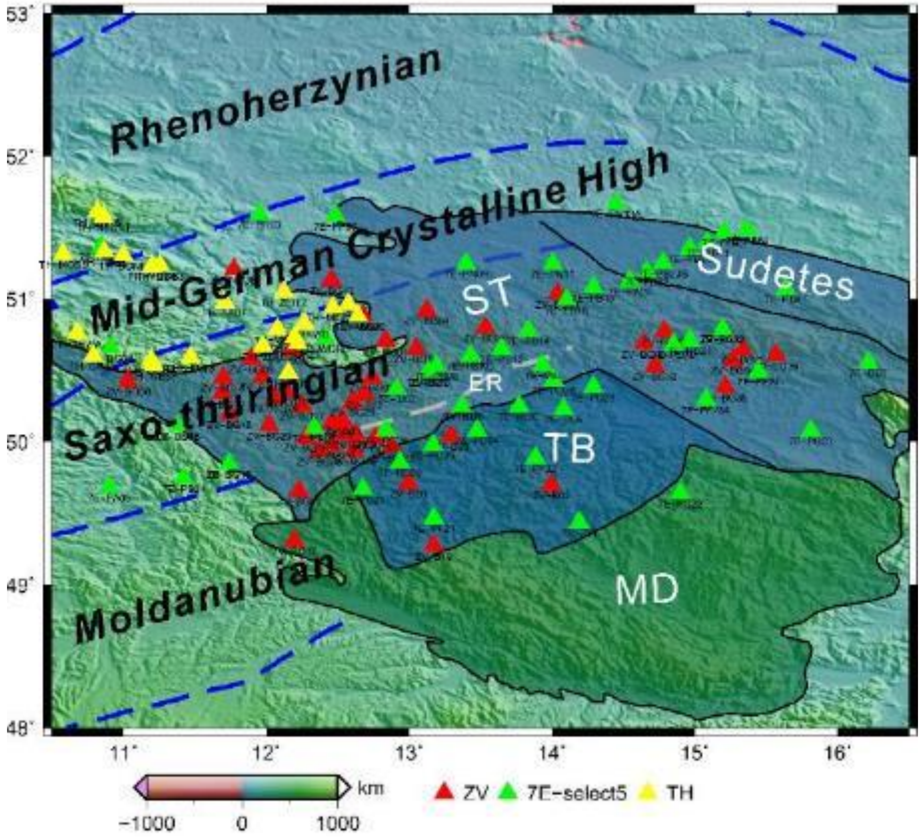


Northwest of Bohemian Massif



ST: Saxo-thuringian of Bohemian Massif

TB: Tepla-Barrandian of Bohemian Massif

MD: Moldanubian of Bohemian Massif

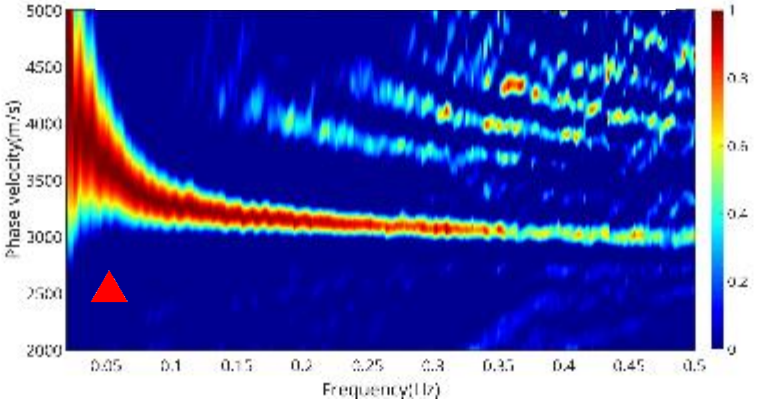
ER: Eger Rift

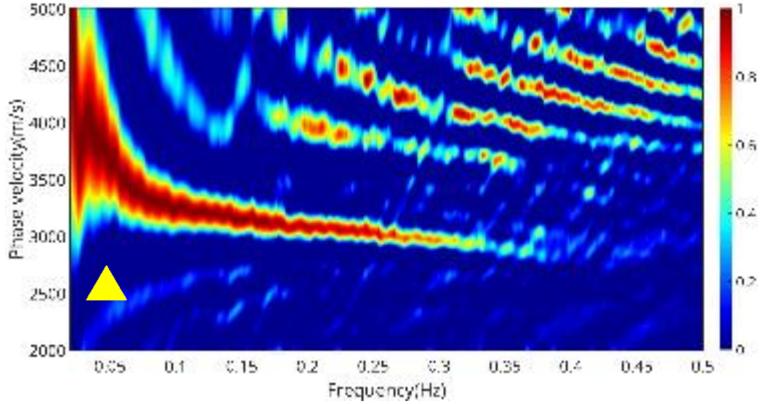
▲ 2001.1-2005.12

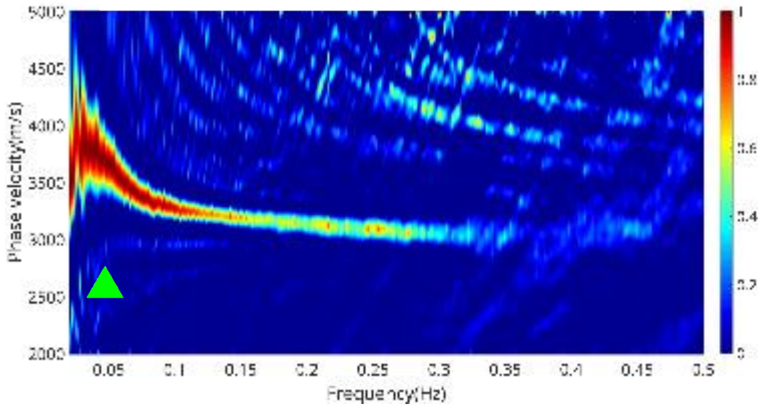
▲ 2017.1-2017.12

▲ 2007.1-2007.12

(Data from IRIS)

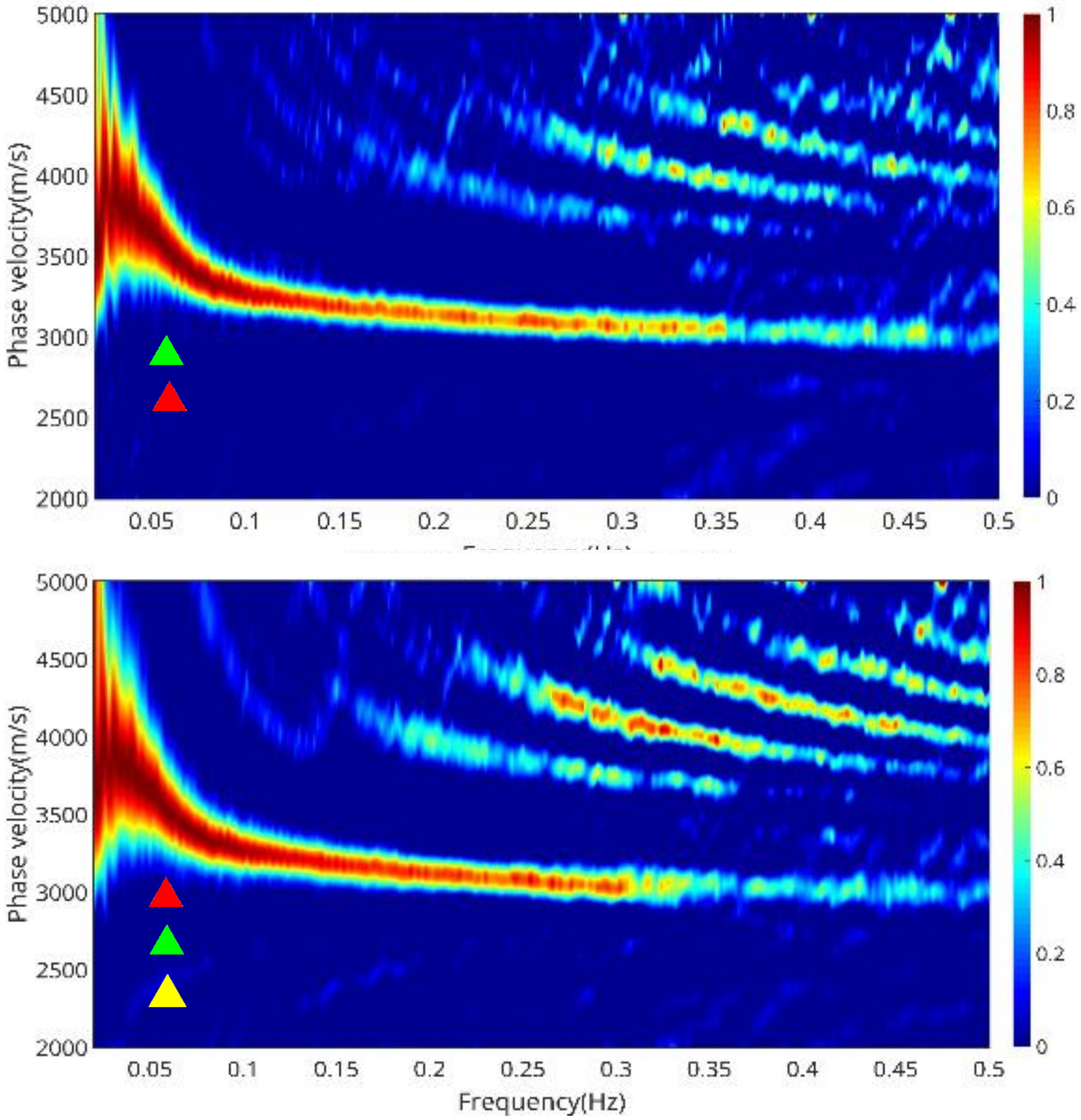


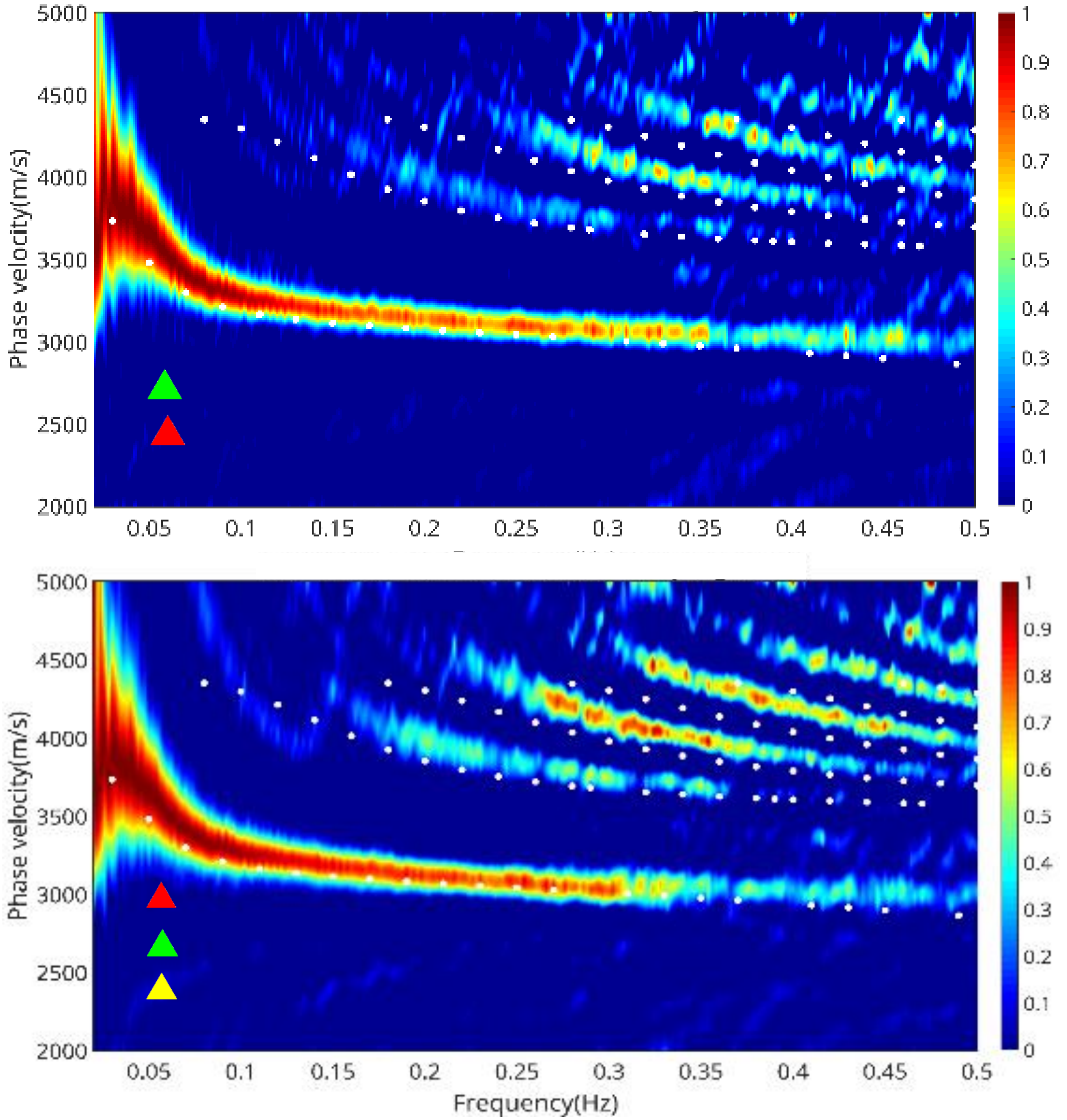




Networks Combination

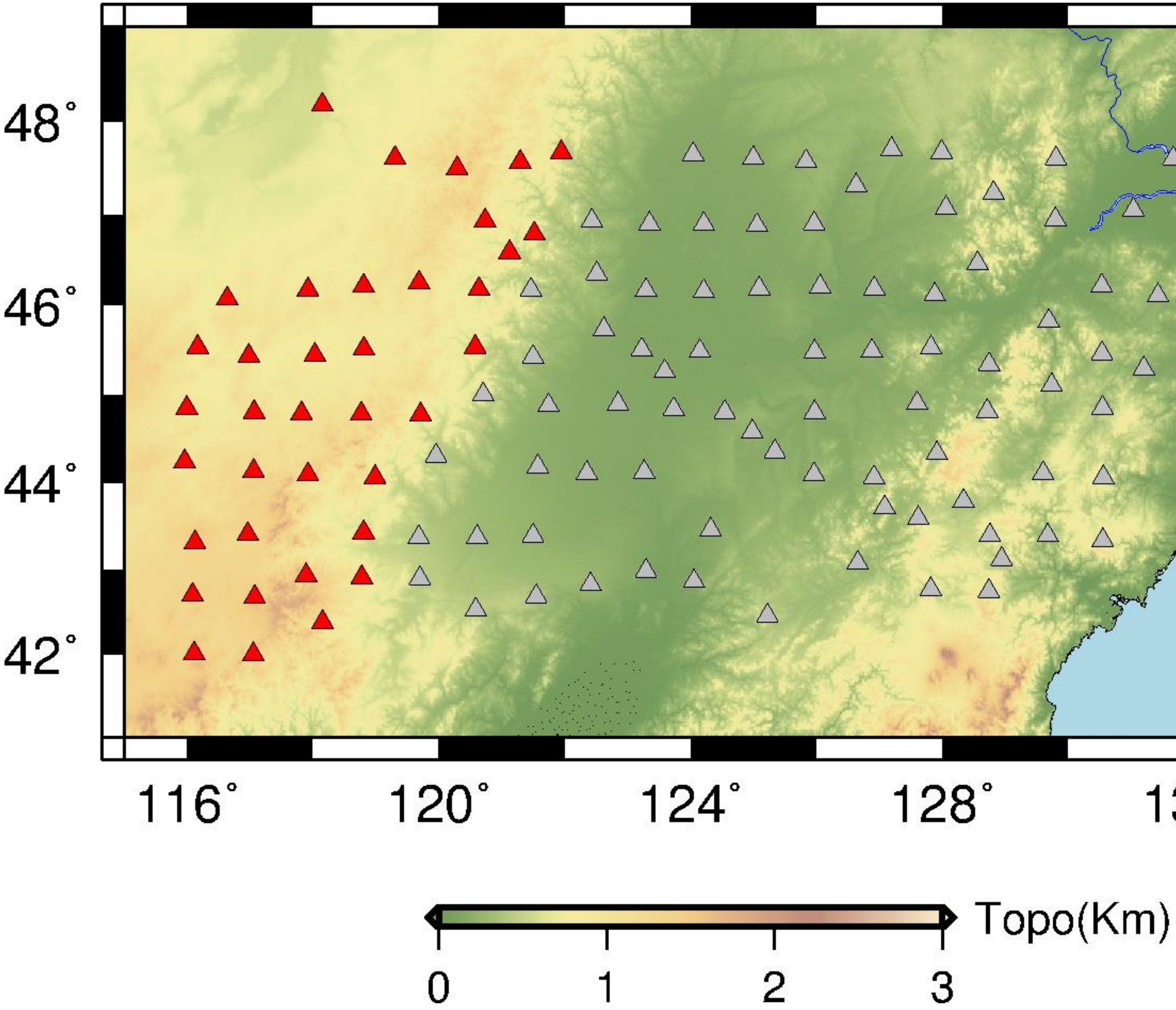
Compared with Lv *et al* (2019)



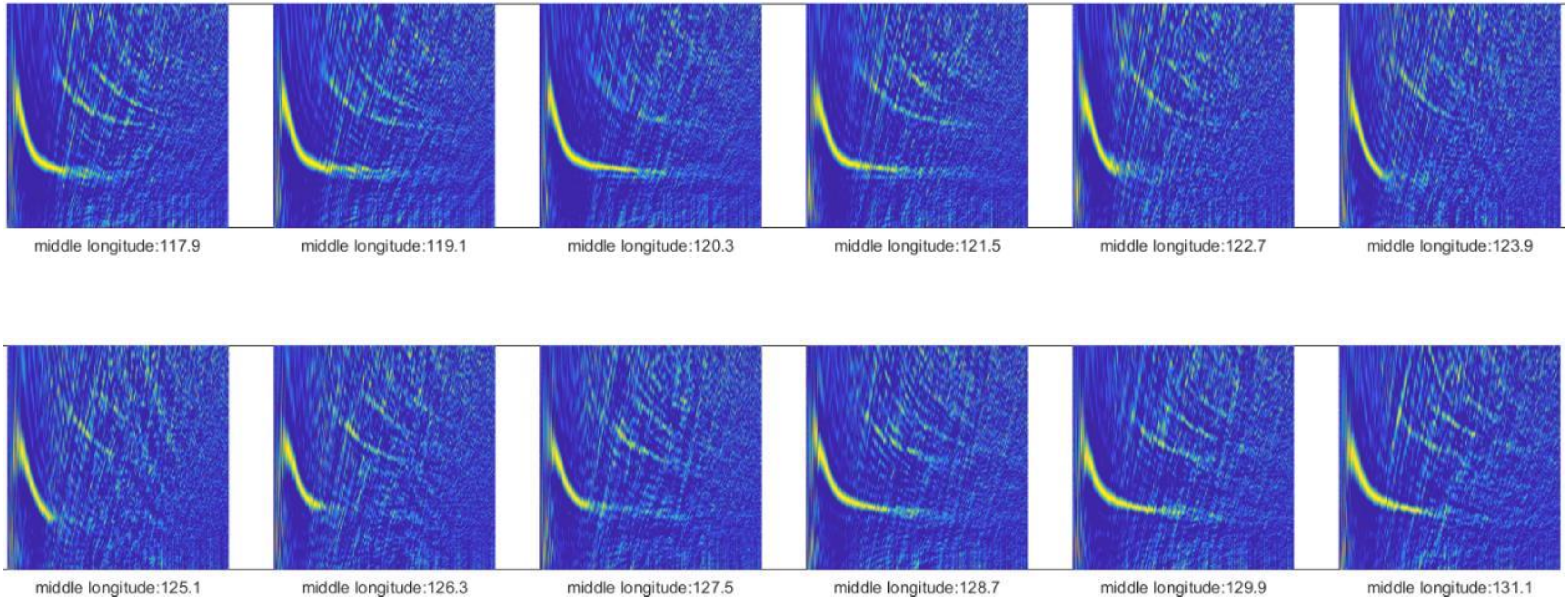


Northeastern China

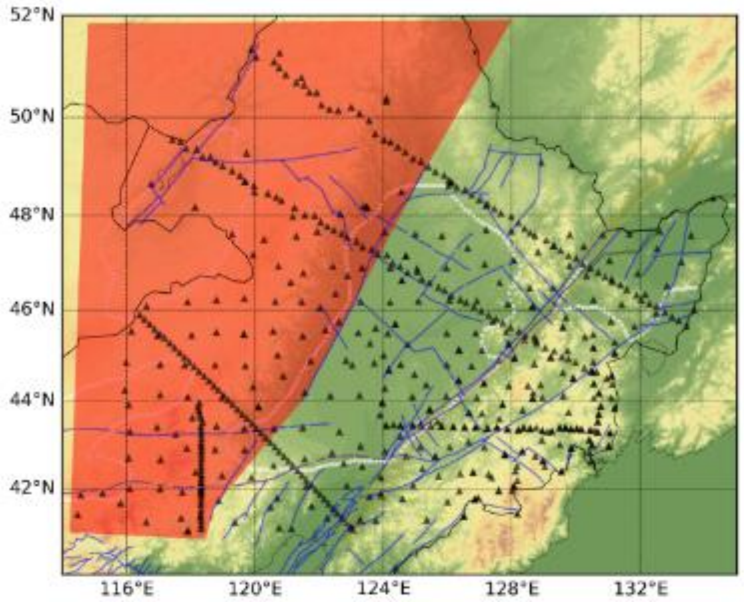
Slice have ~80% stations overlap

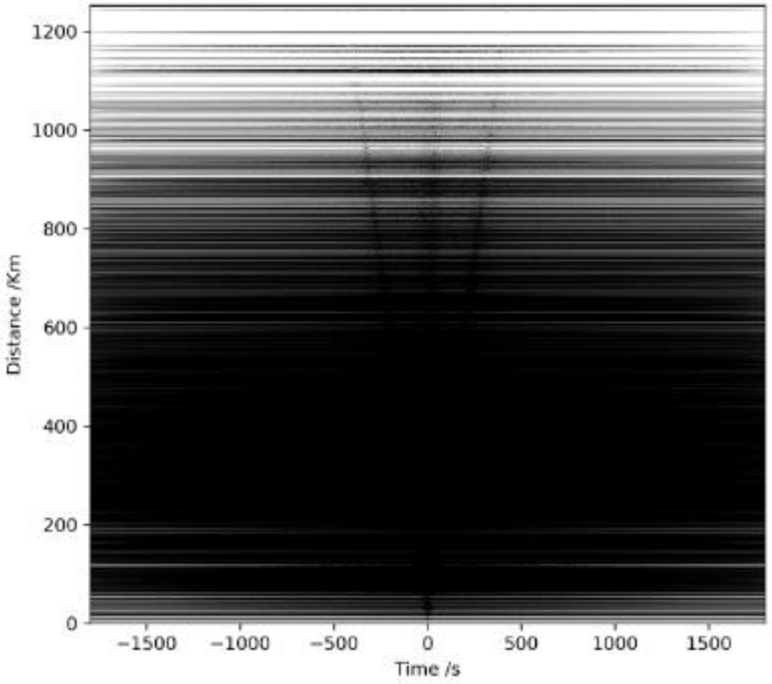


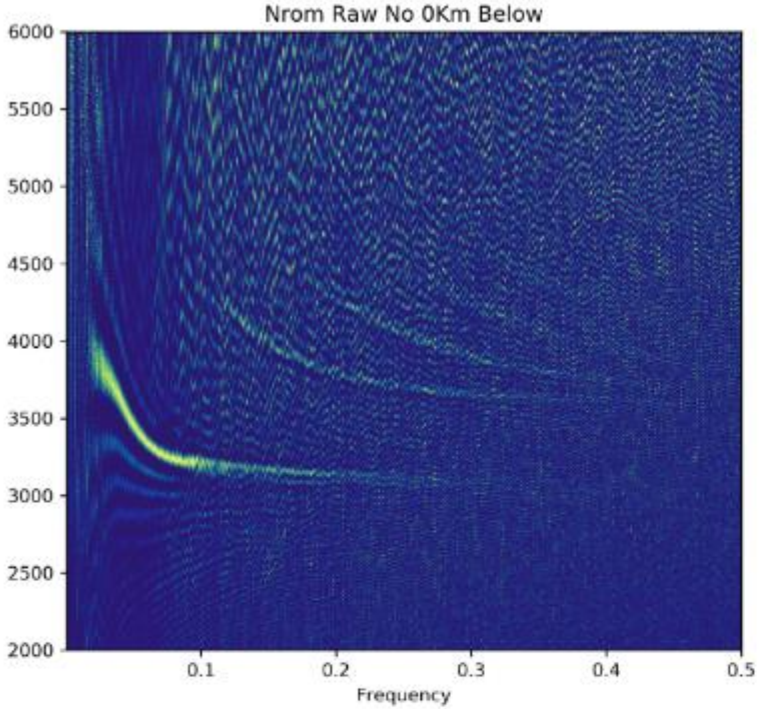
(Data from China Seismic Data Center/IRIS)

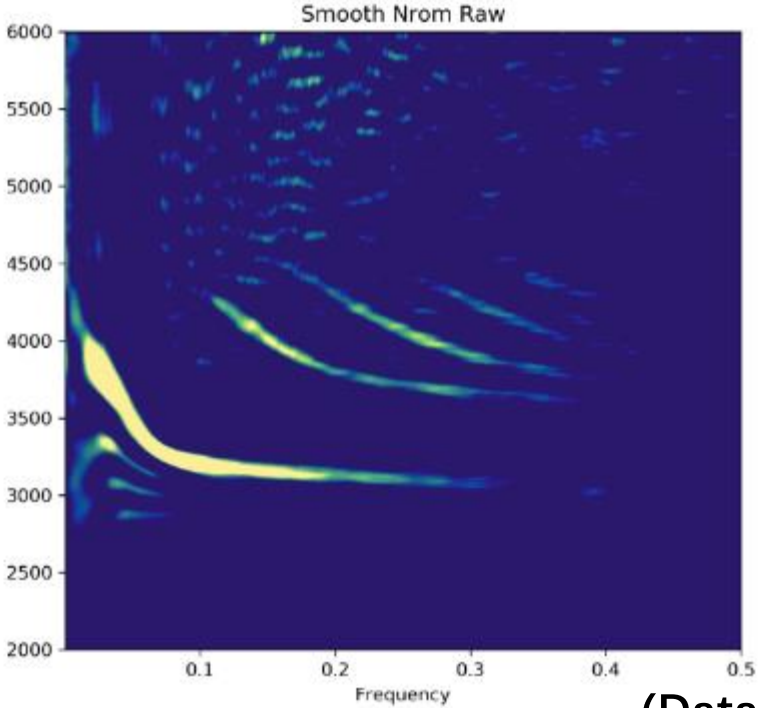

middle longitude:117.9
middle longitude:119.1
middle longitude:120.3
middle longitude:121.5
middle longitude:122.7
middle longitude:123.9
middle longitude:125.1
middle longitude:126.3
middle longitude:127.5
middle longitude:128.7
middle longitude:129.9
middle longitude:131.1

Northeastern China









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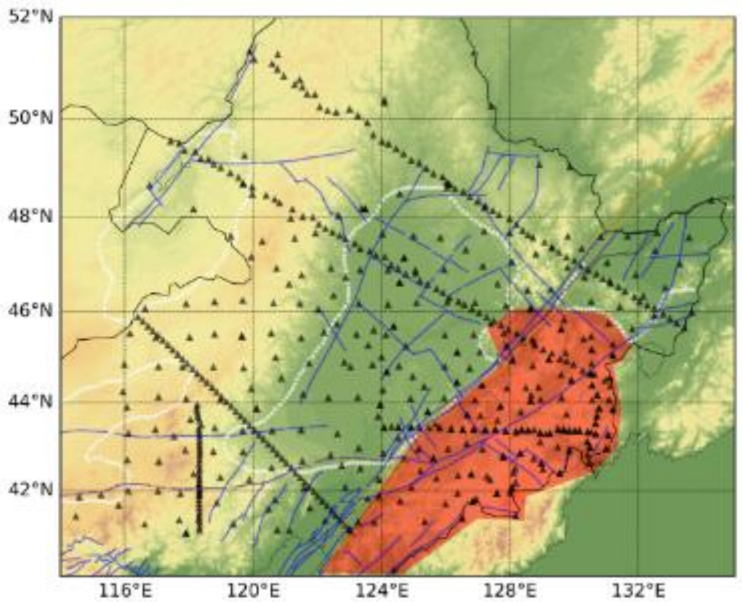
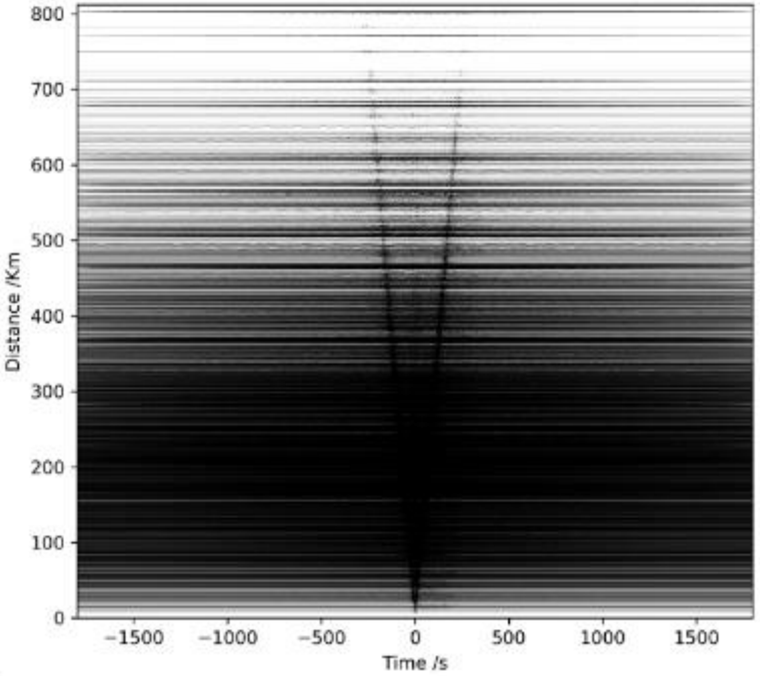
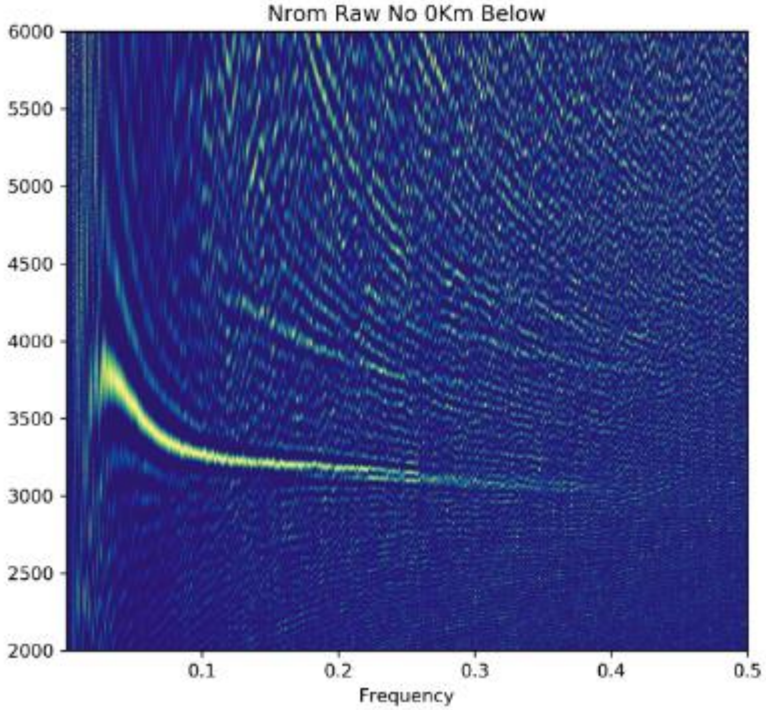
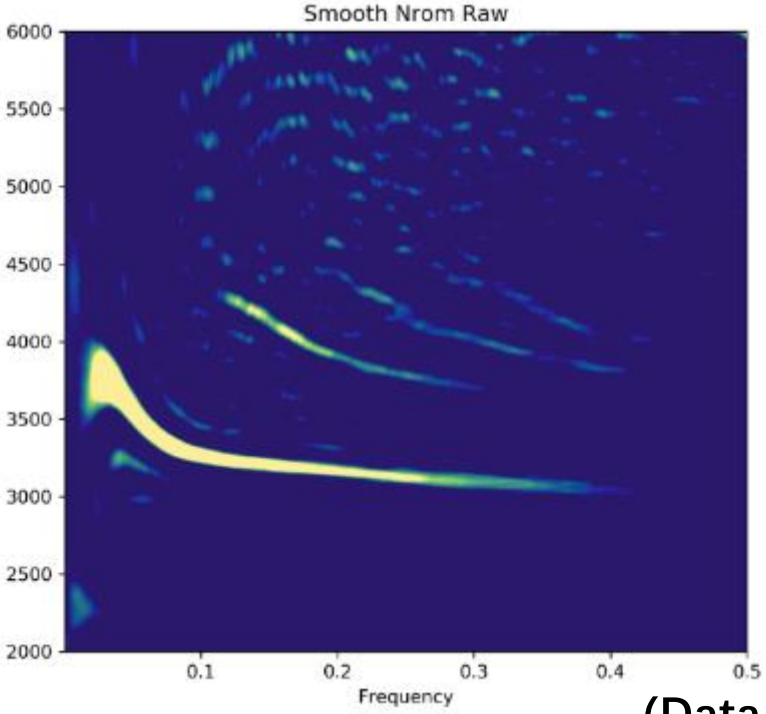
Northeastern China









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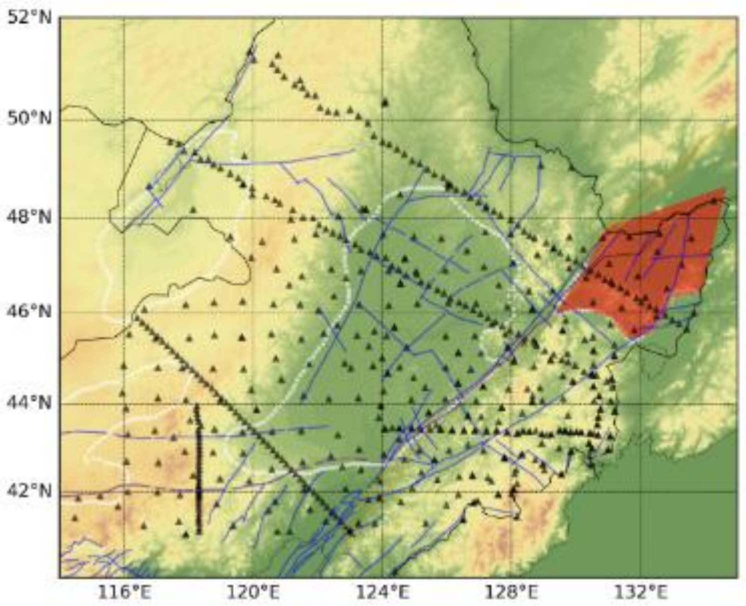
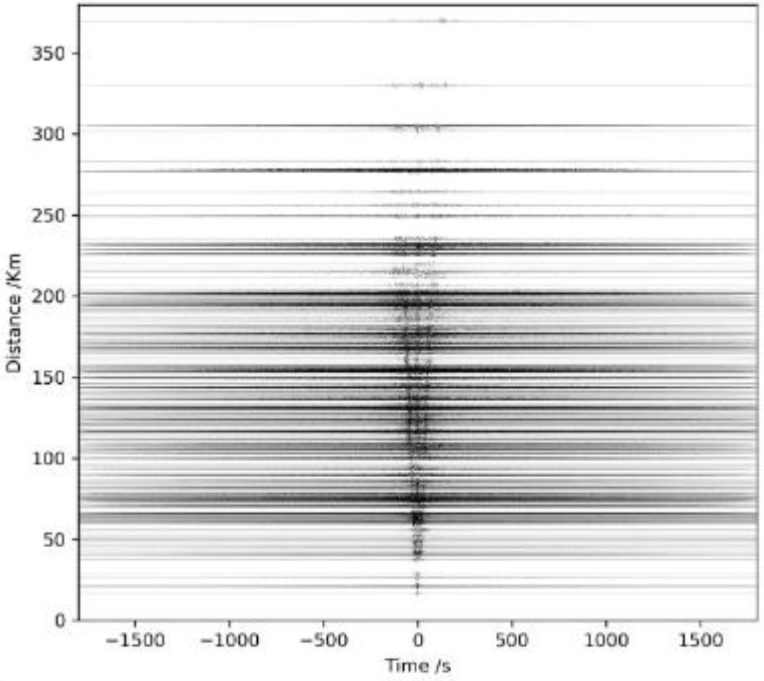
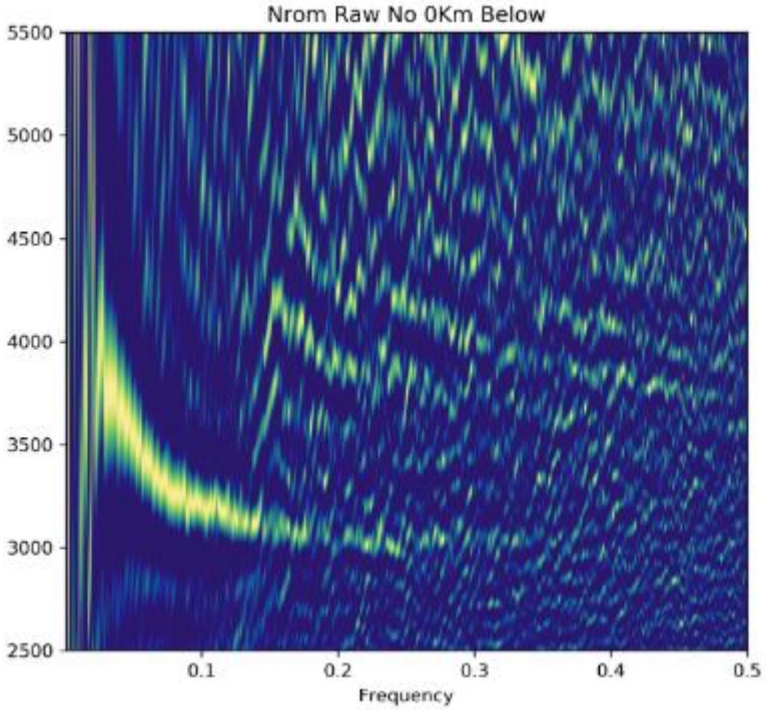
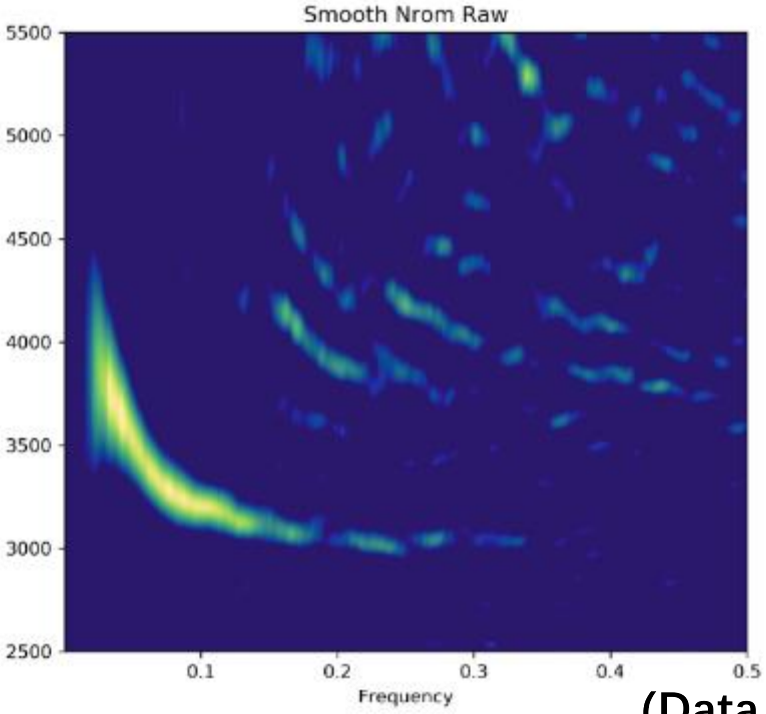


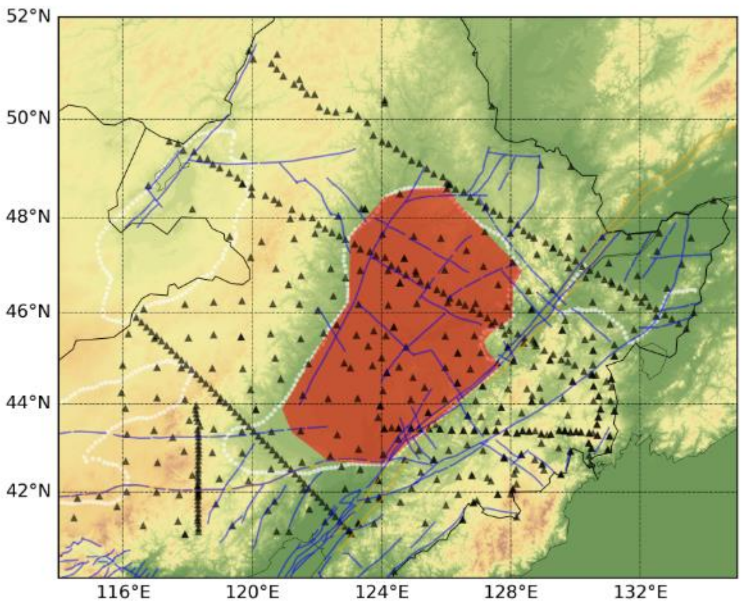


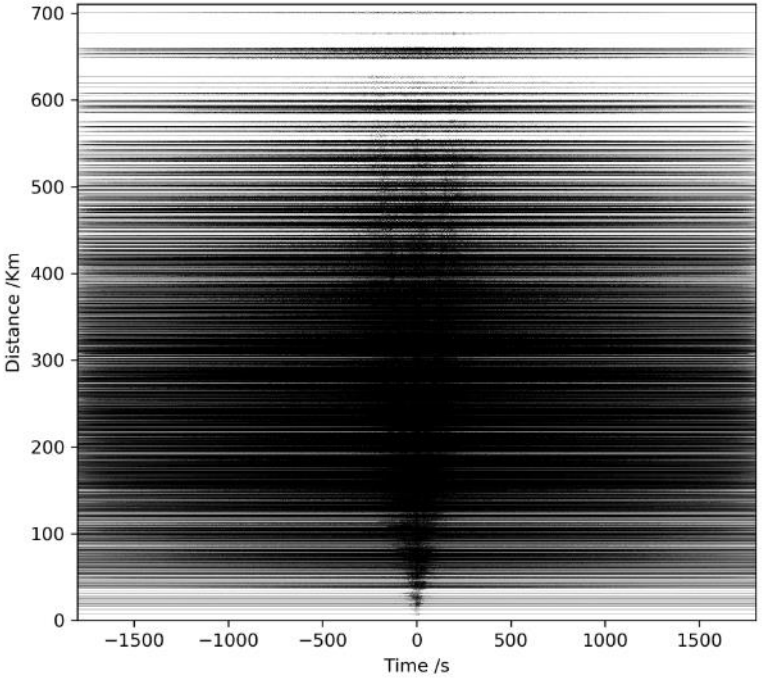


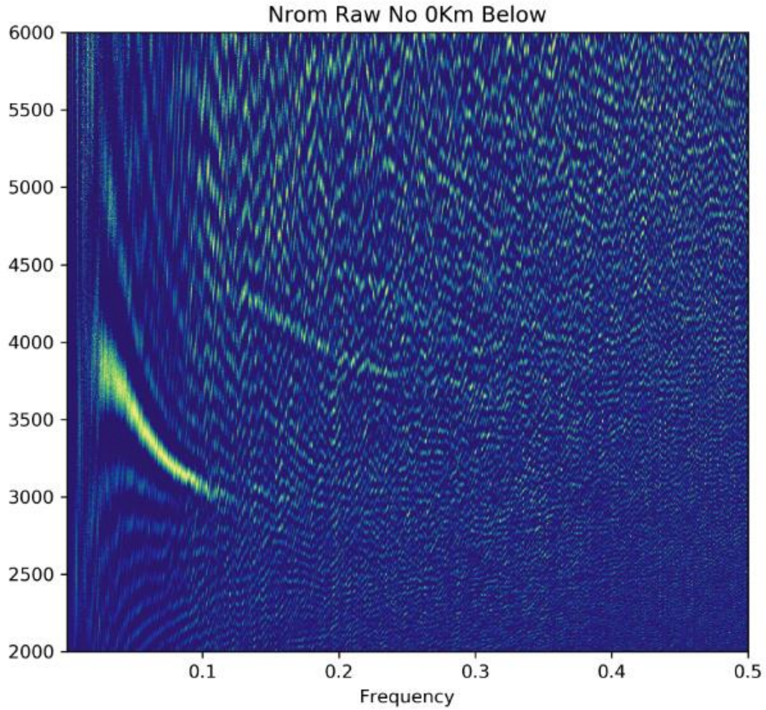


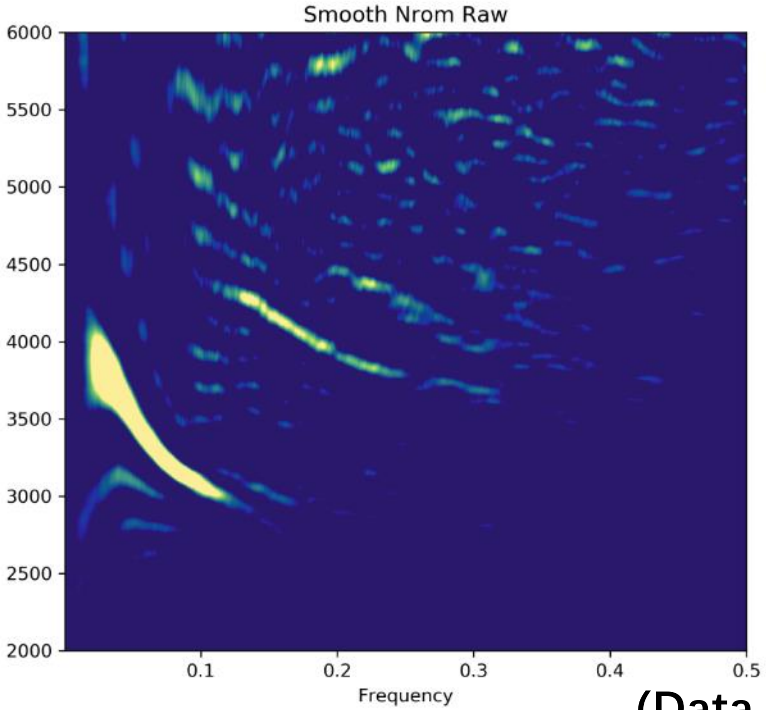
(Data from China Seismic Data Center/IRIS)

Northeastern China









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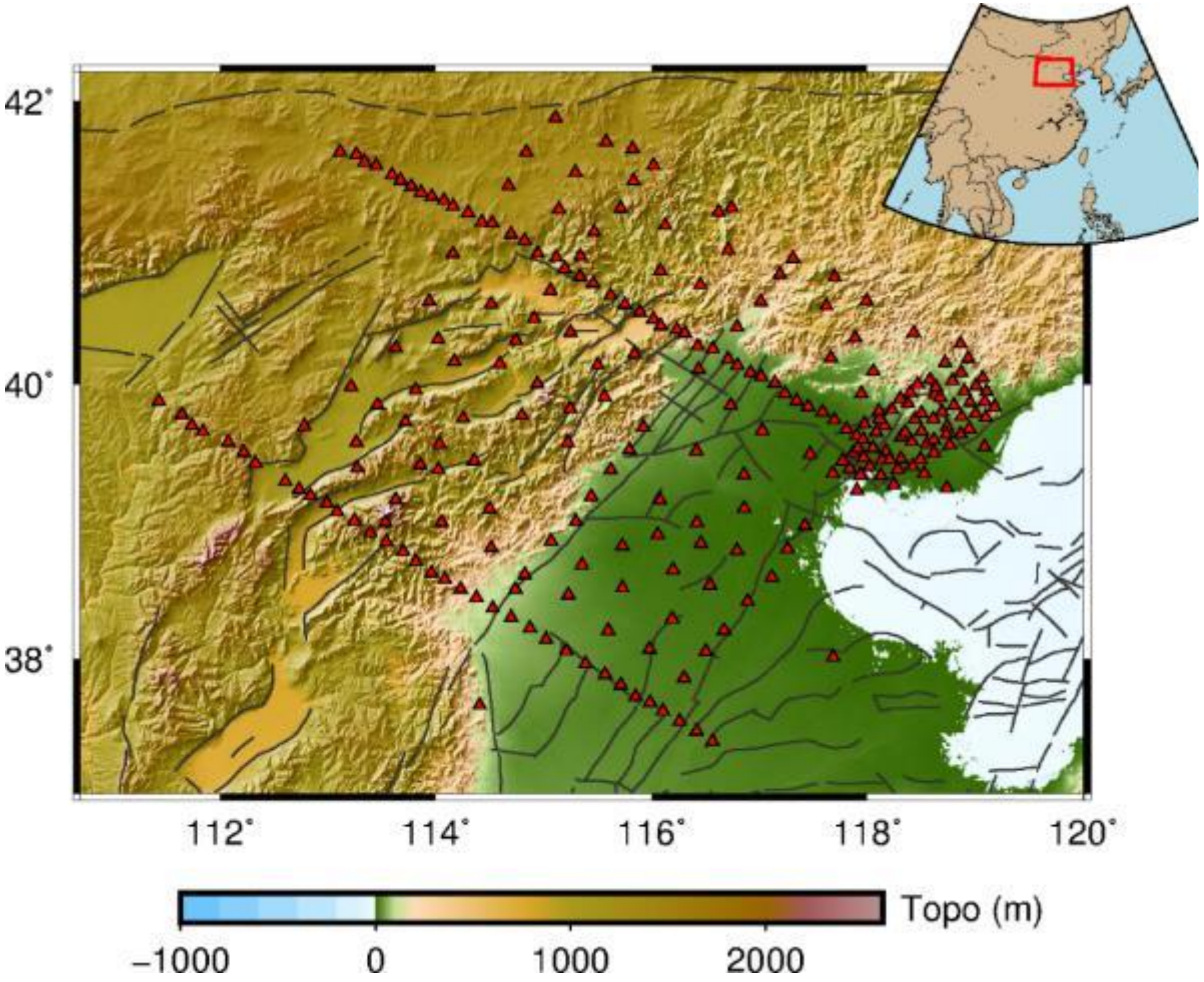
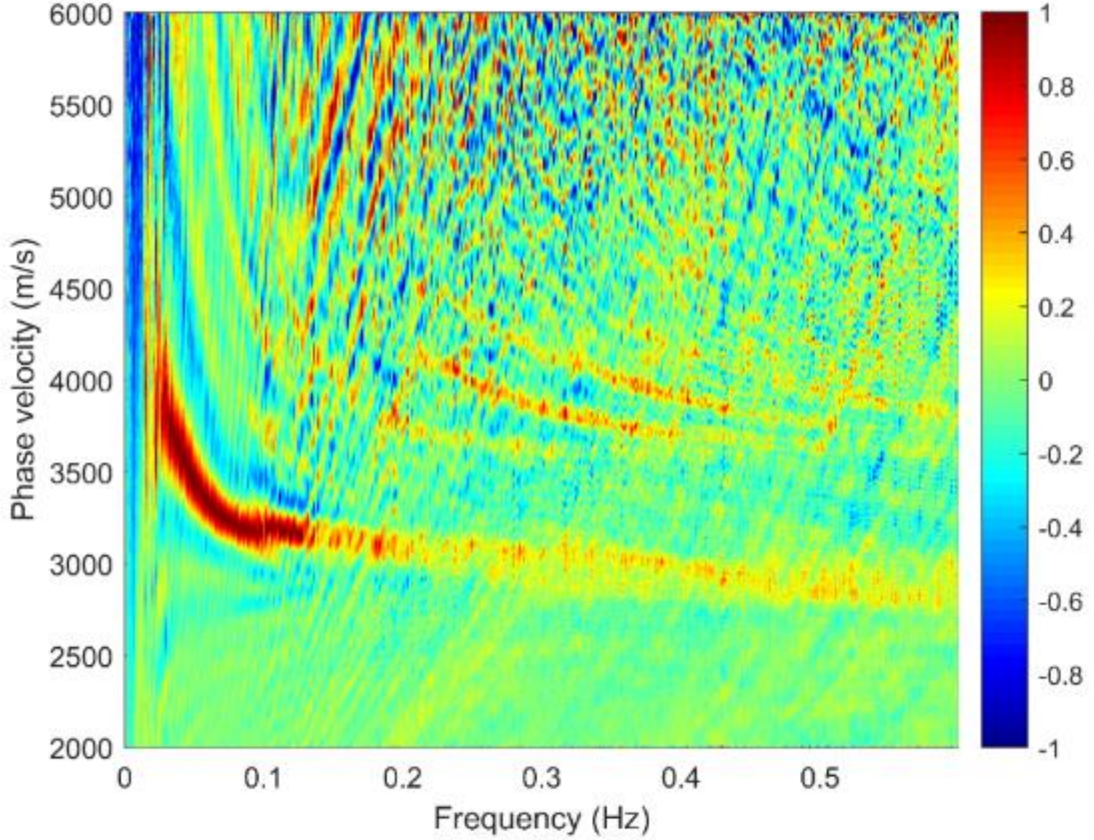
Northern China

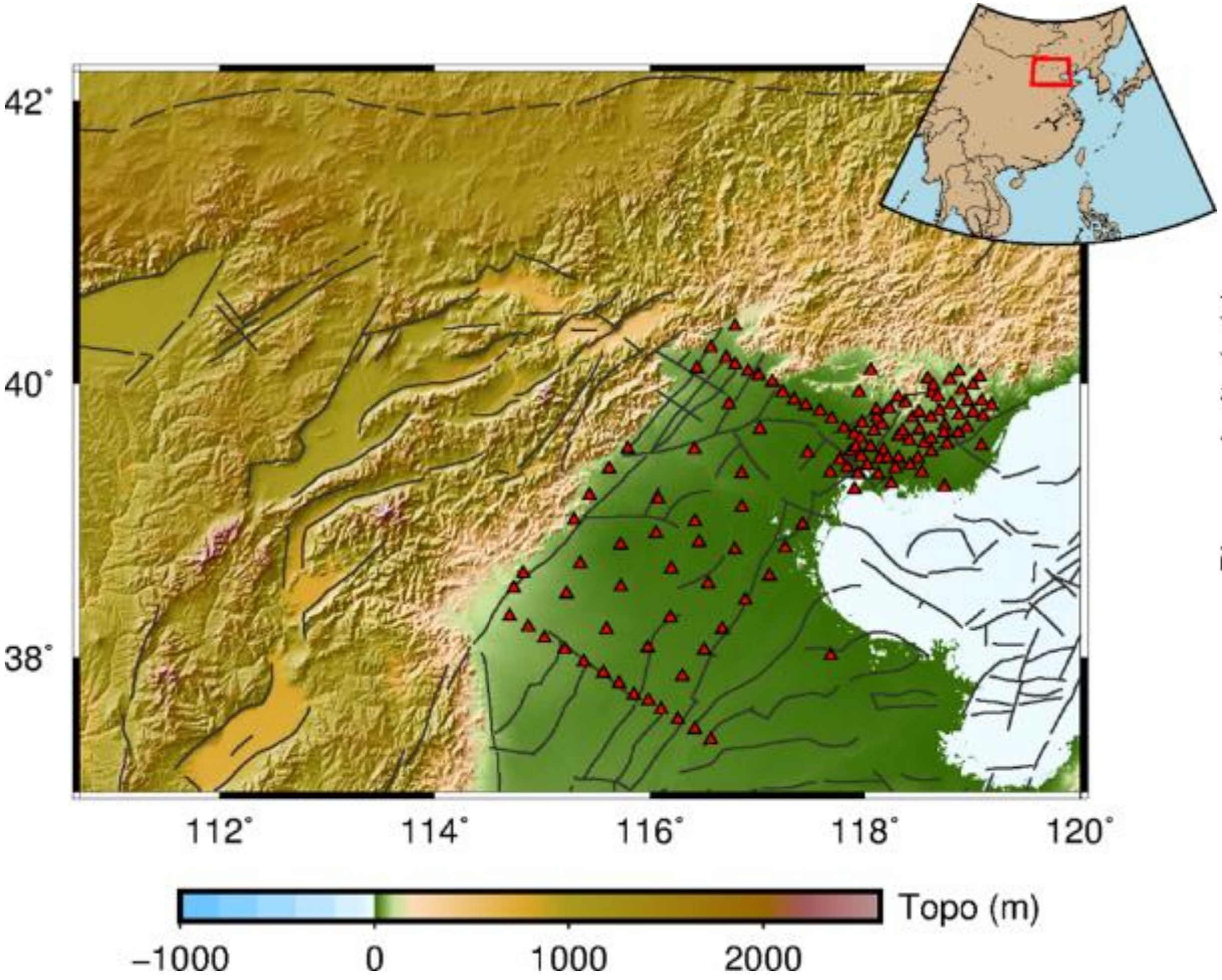


Data 2007

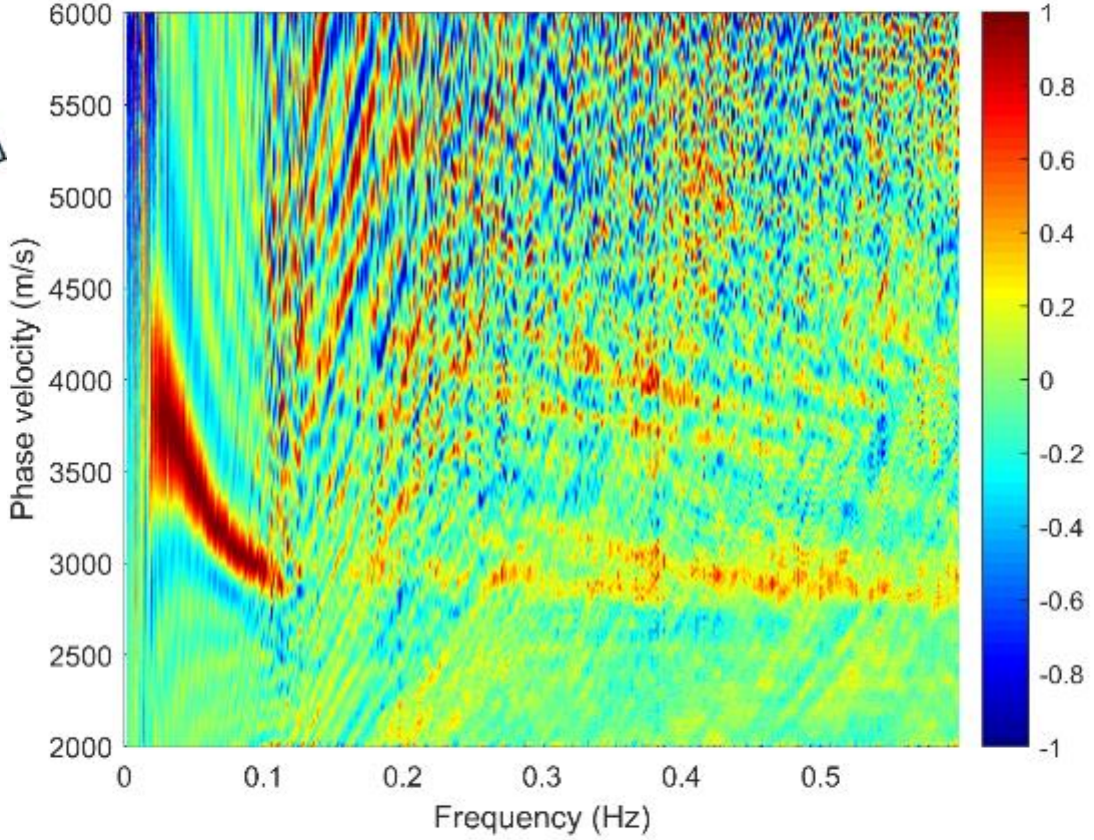


(Data from China Seismic Data Center/IRIS)

Northern China



Data 2007



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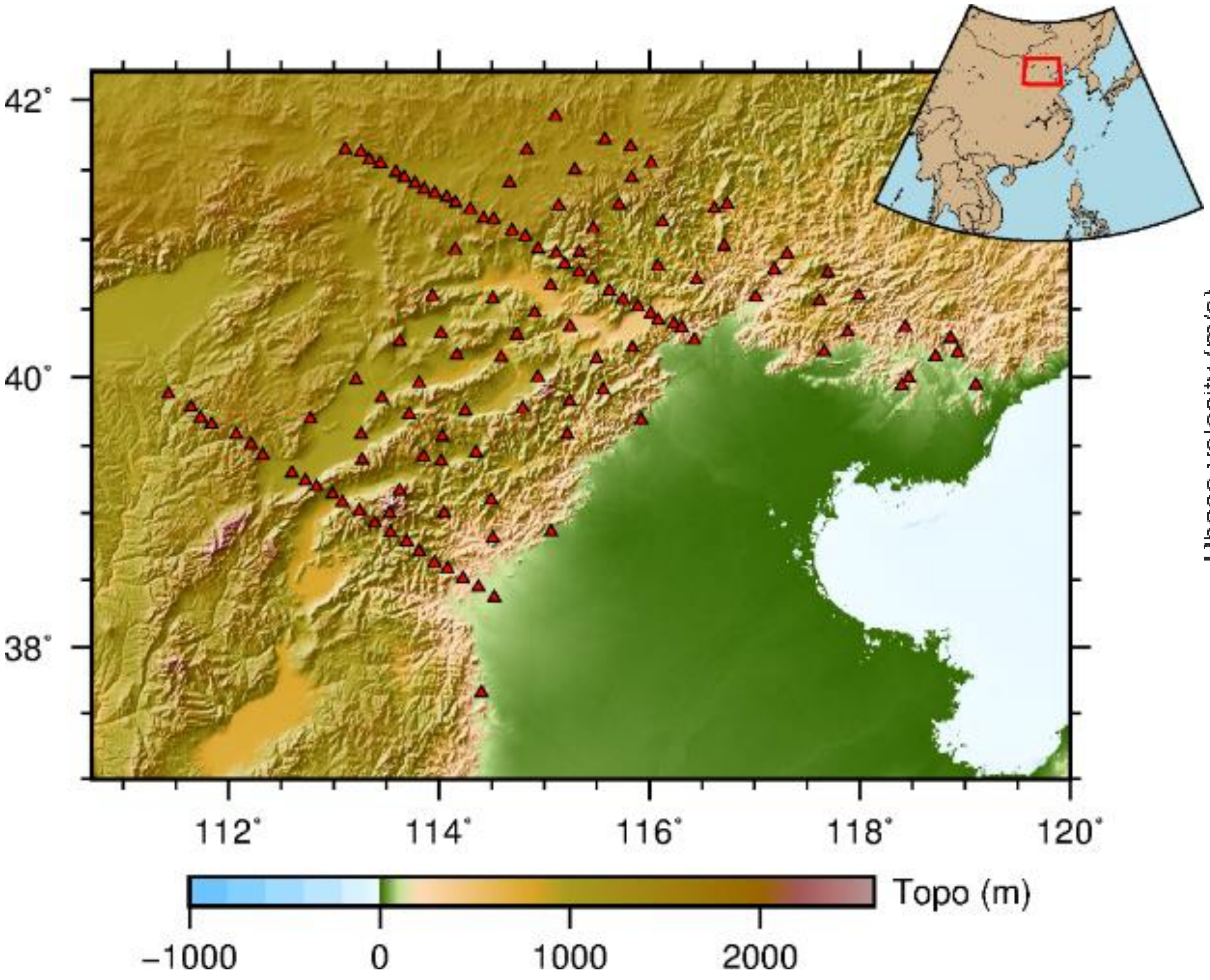
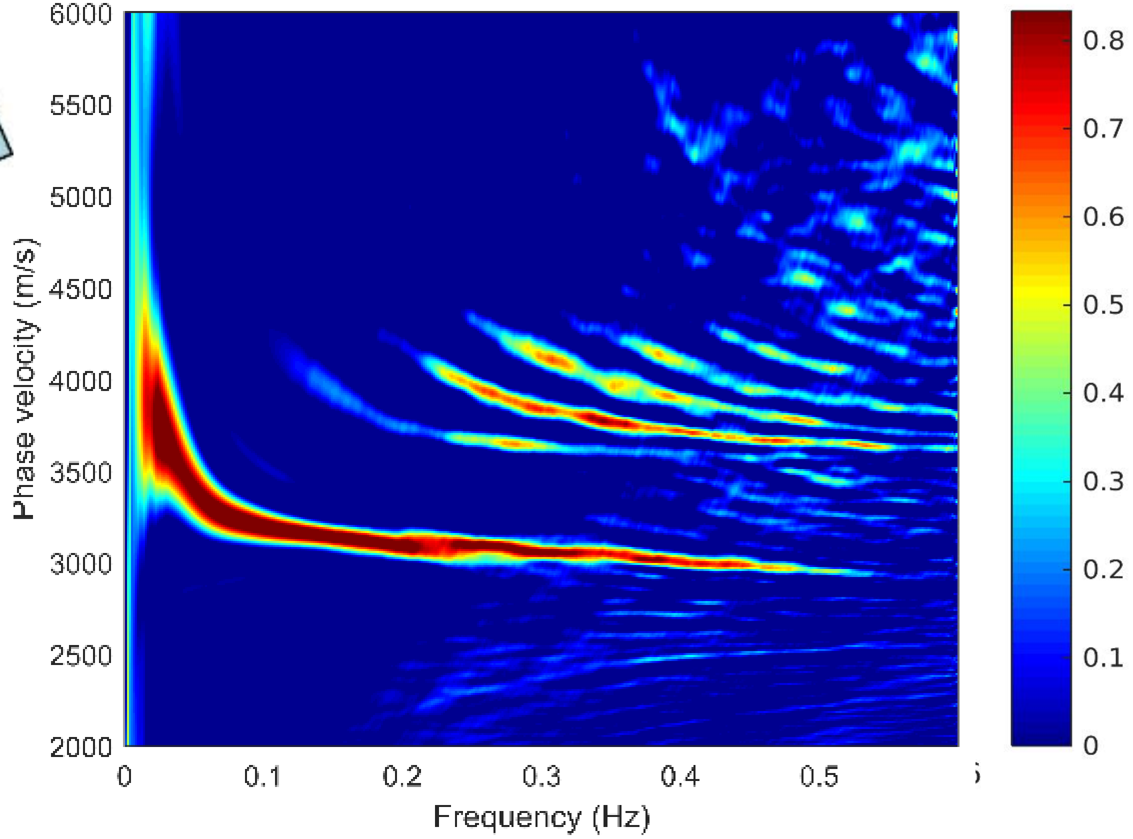
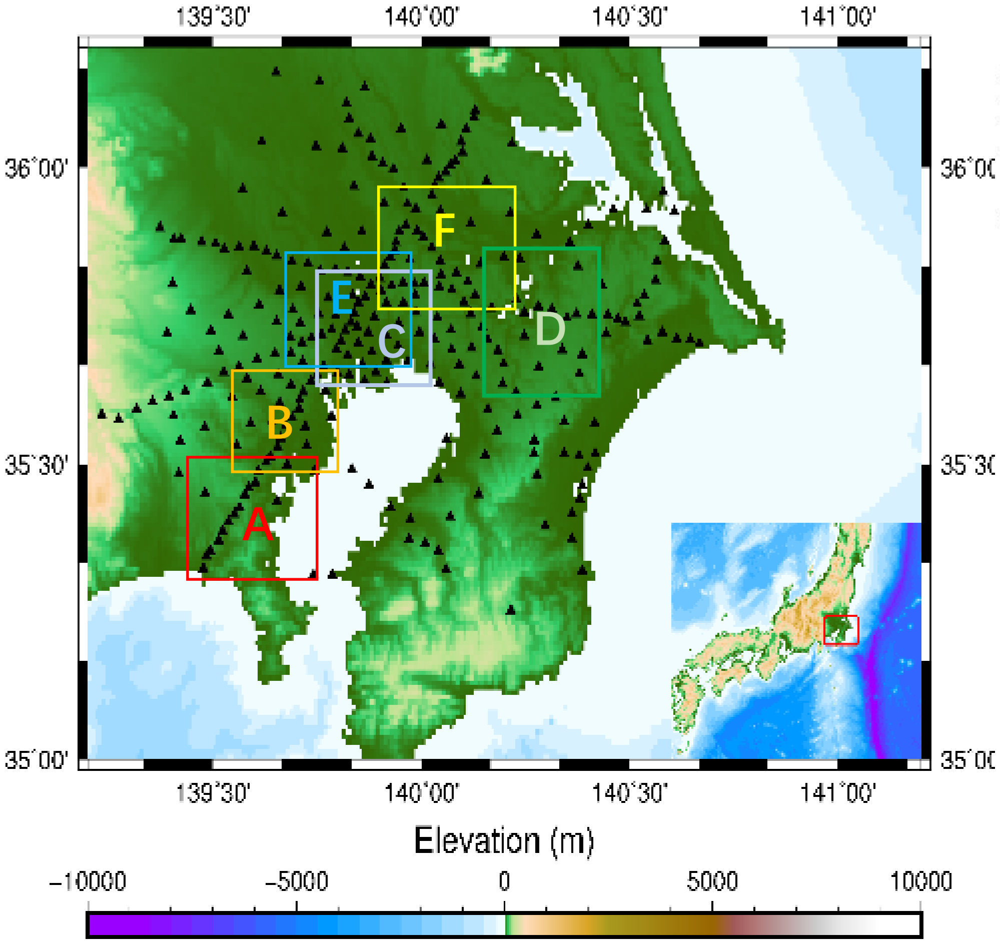


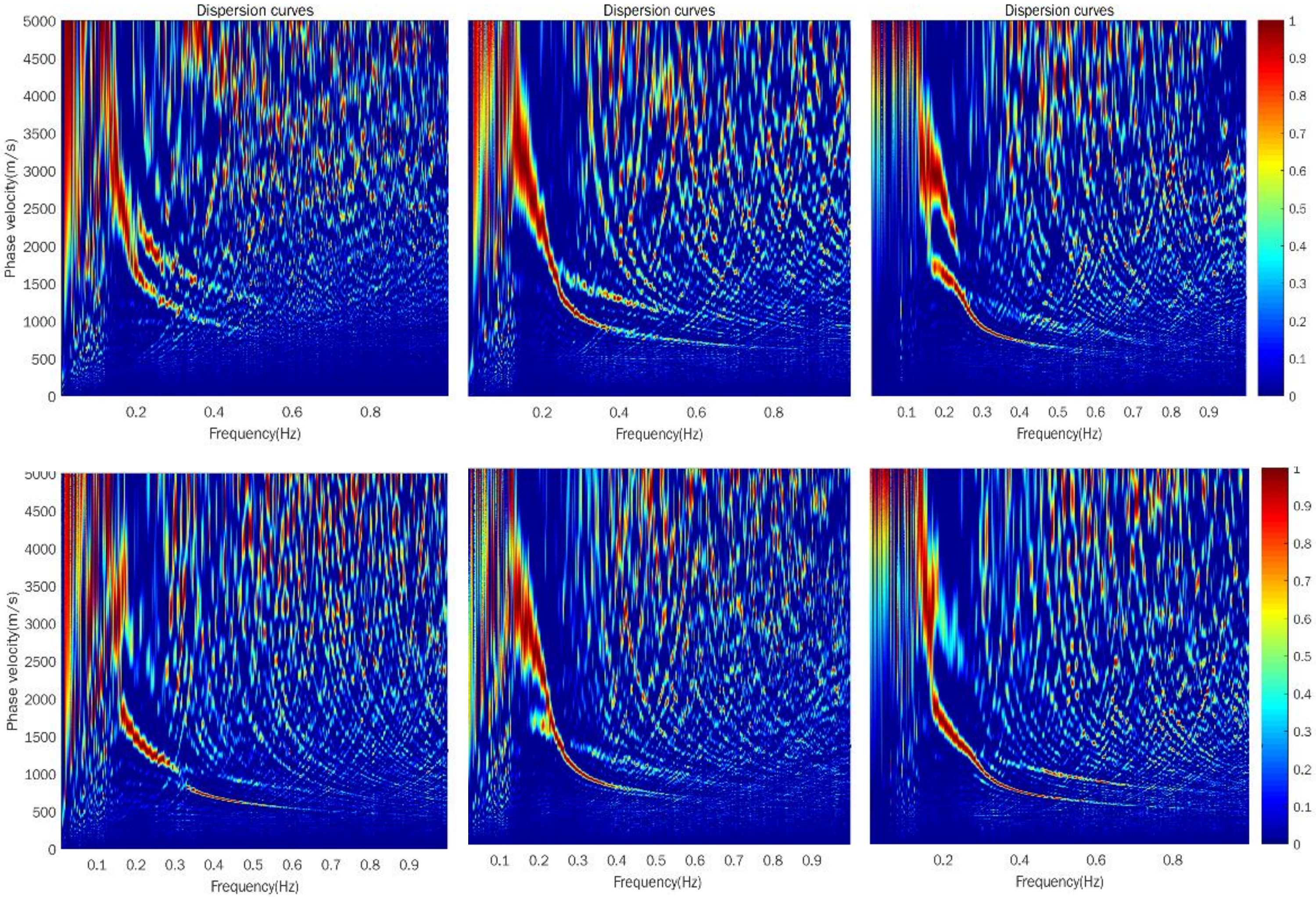
Data 2007



(Data from China Seismic Data Center/IRIS)

Kanto Basin, JP

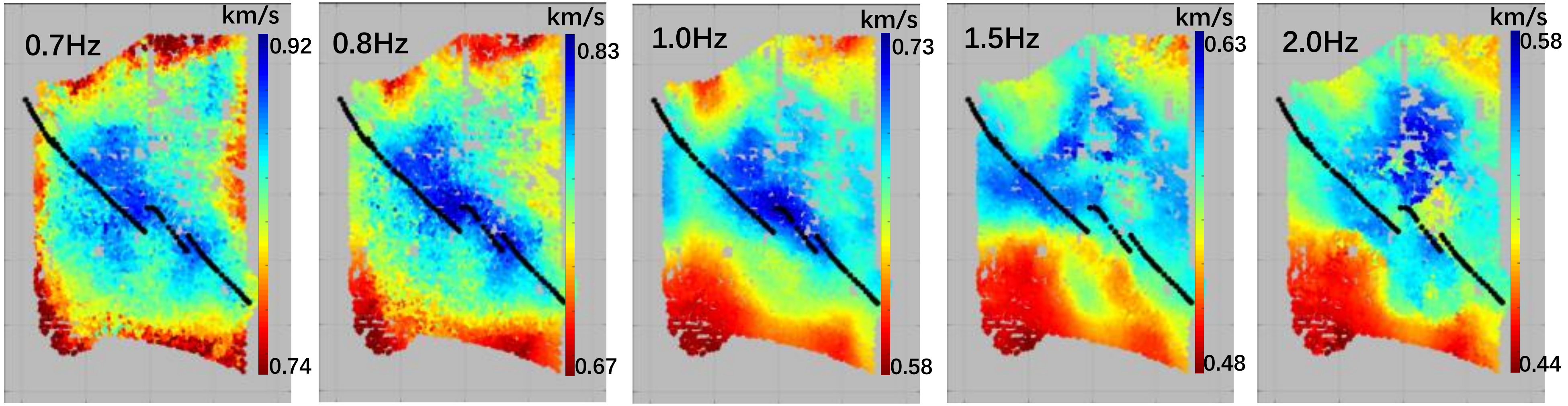




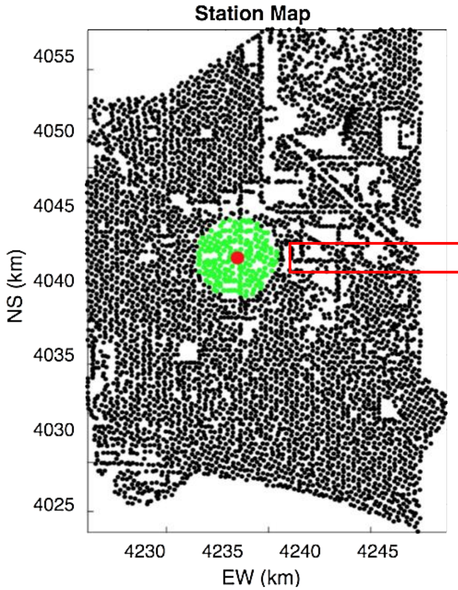
Total number of Stations: **298**
Data used: **2018.1.1-2018.6.30**
(from Open Data of NIED, Japan)

Sub-area	A	B	C	D	E	F
Number of Stations	19	29	44	24	39	32

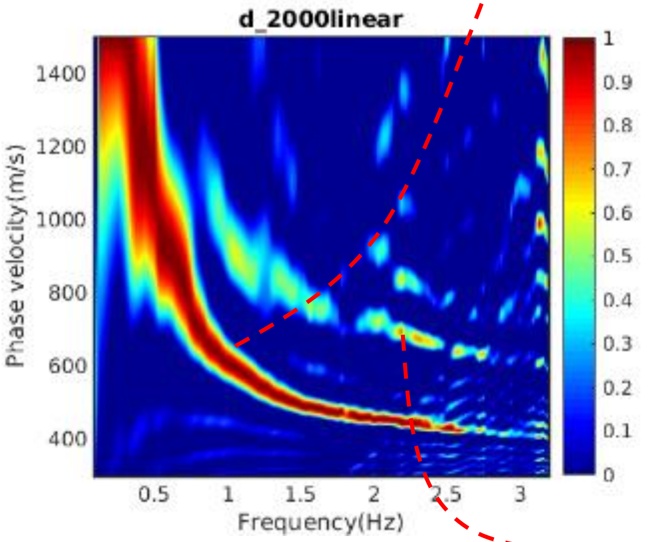
Re-processing of the Long Beach experimental data by F-J Method

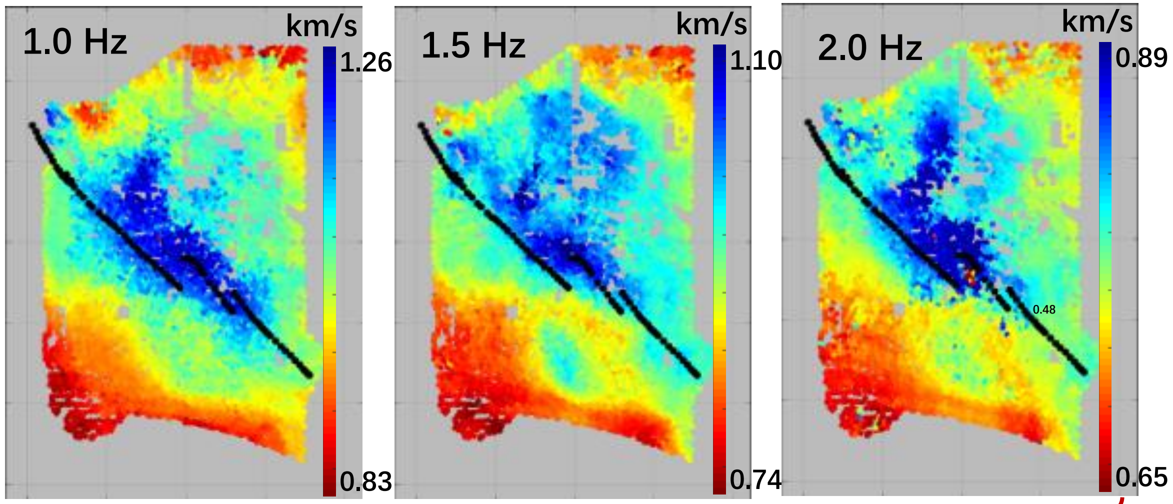


Phase velocity of fundamental mode (0th mode)



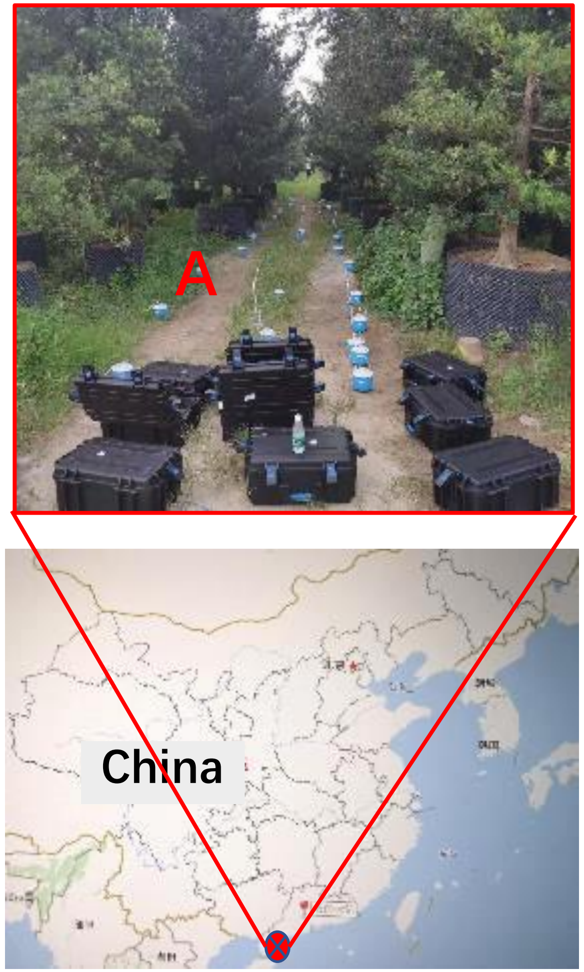
(e.g., Lin et al., 2013)



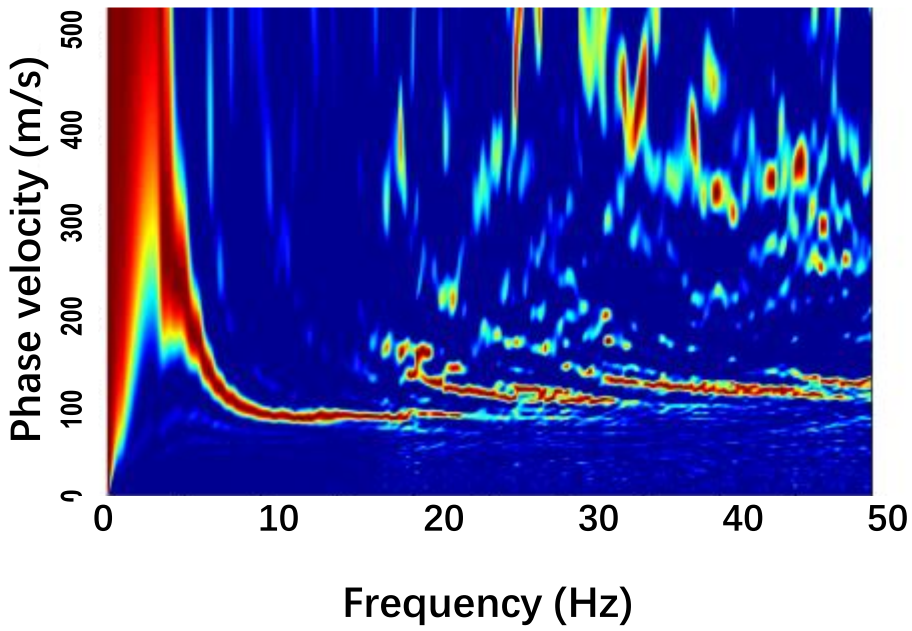


Phase velocity of first higher mode (1st mode)

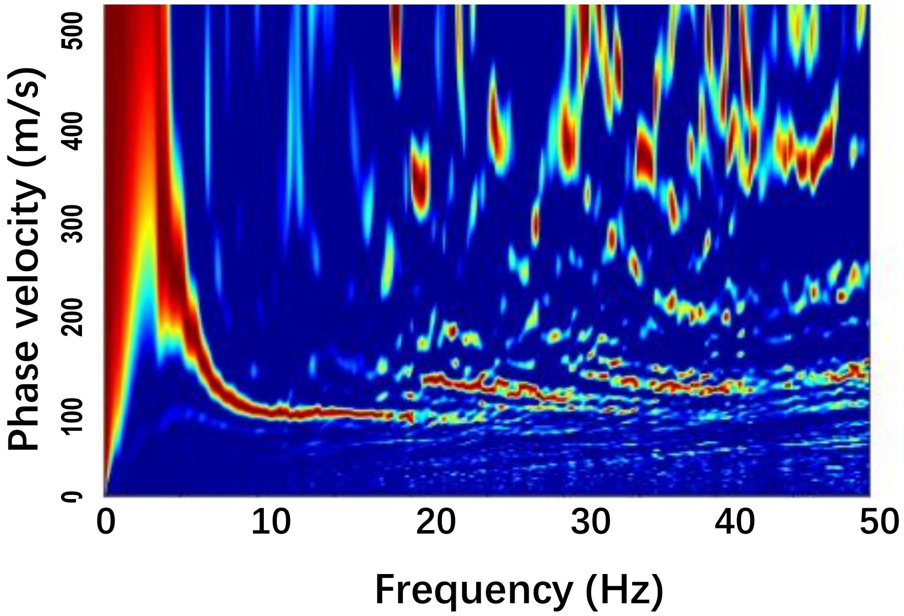
Application in Geo-Engineering Survey:



20 stations survey



10 stations survey



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Inversion of Multi-modal dispersion curves

- Objective function of multi-modal dispersion curves：

$$f(\boldsymbol{m}) = \sum_k \frac{a_k}{n_k} \left\{ \sum_i [c_{ik}^s(\boldsymbol{m}) - c_{ik}^o]^2 \right\}$$

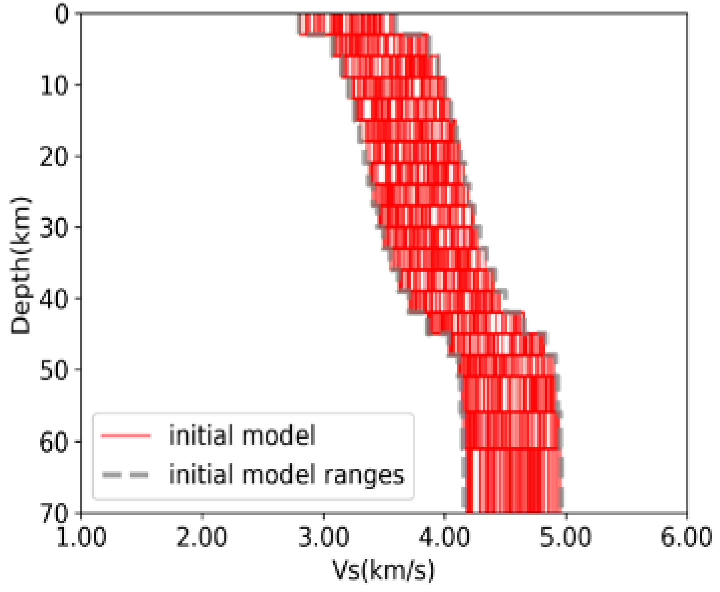
- Running each inversion by BFGS algorithm,
- then running a number of inversion with randomly distributed initial model within a given sub-model space,
- Final estimated model is calculated by a weighted sum：

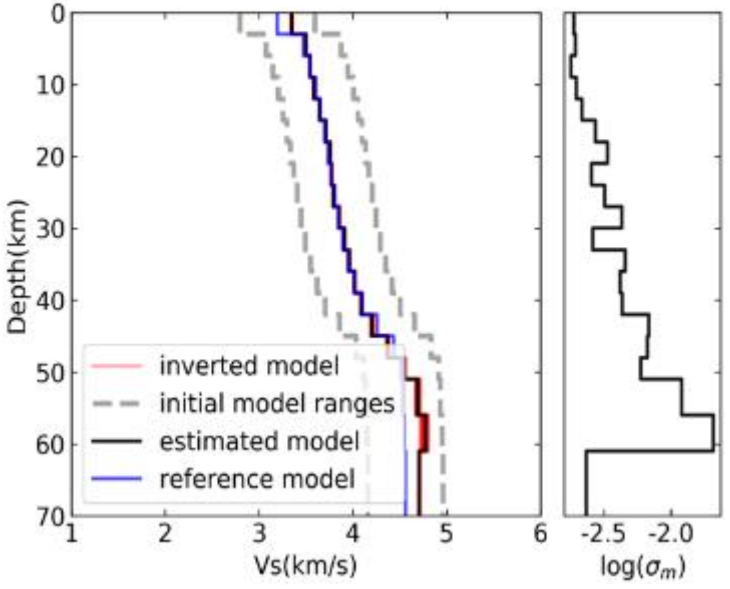
$$\widehat{\boldsymbol{m}} = \frac{1}{\sum_{j=1}^{M} w(\boldsymbol{m}_j)} \sum_{j=1}^{M} w(\boldsymbol{m}_j)\, \boldsymbol{m}_j \ ,$$

$$w(\boldsymbol{m}_i) = [f_N(\boldsymbol{m}_i)]^{-p}$$

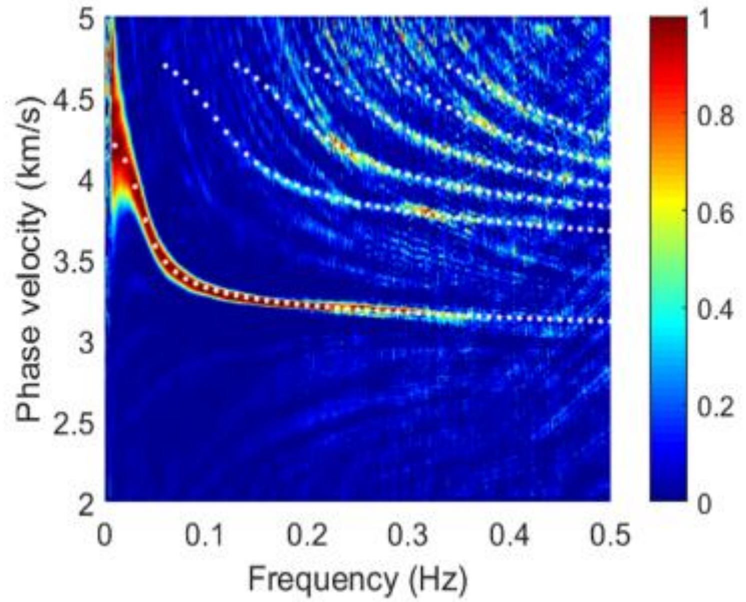
$$\sigma_{\boldsymbol{m}} = \sqrt{\frac{1}{M-1} \sum_{i=1}^{M} (\boldsymbol{m}_i - \widehat{\boldsymbol{m}})^2}$$

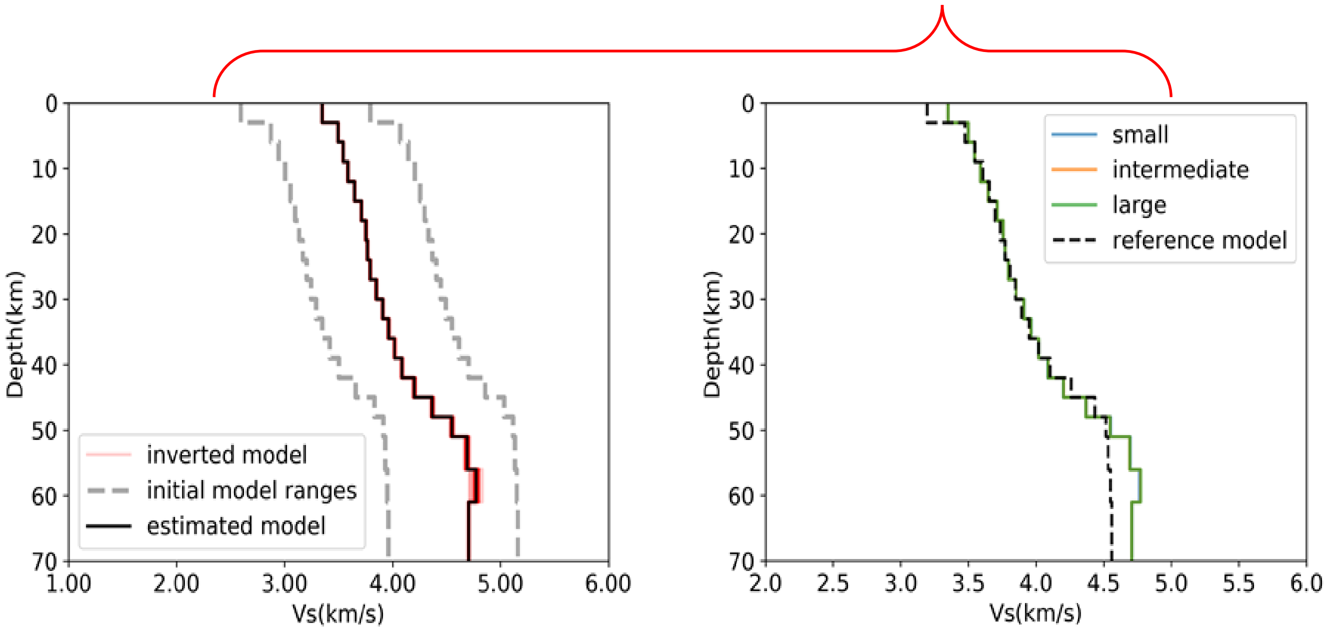
Inversion Results for Central US



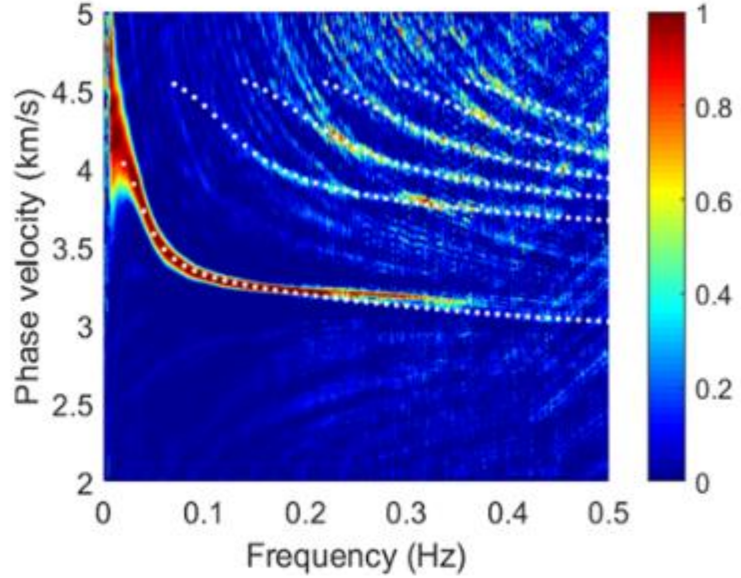


反演后的拟合





反演前的拟合

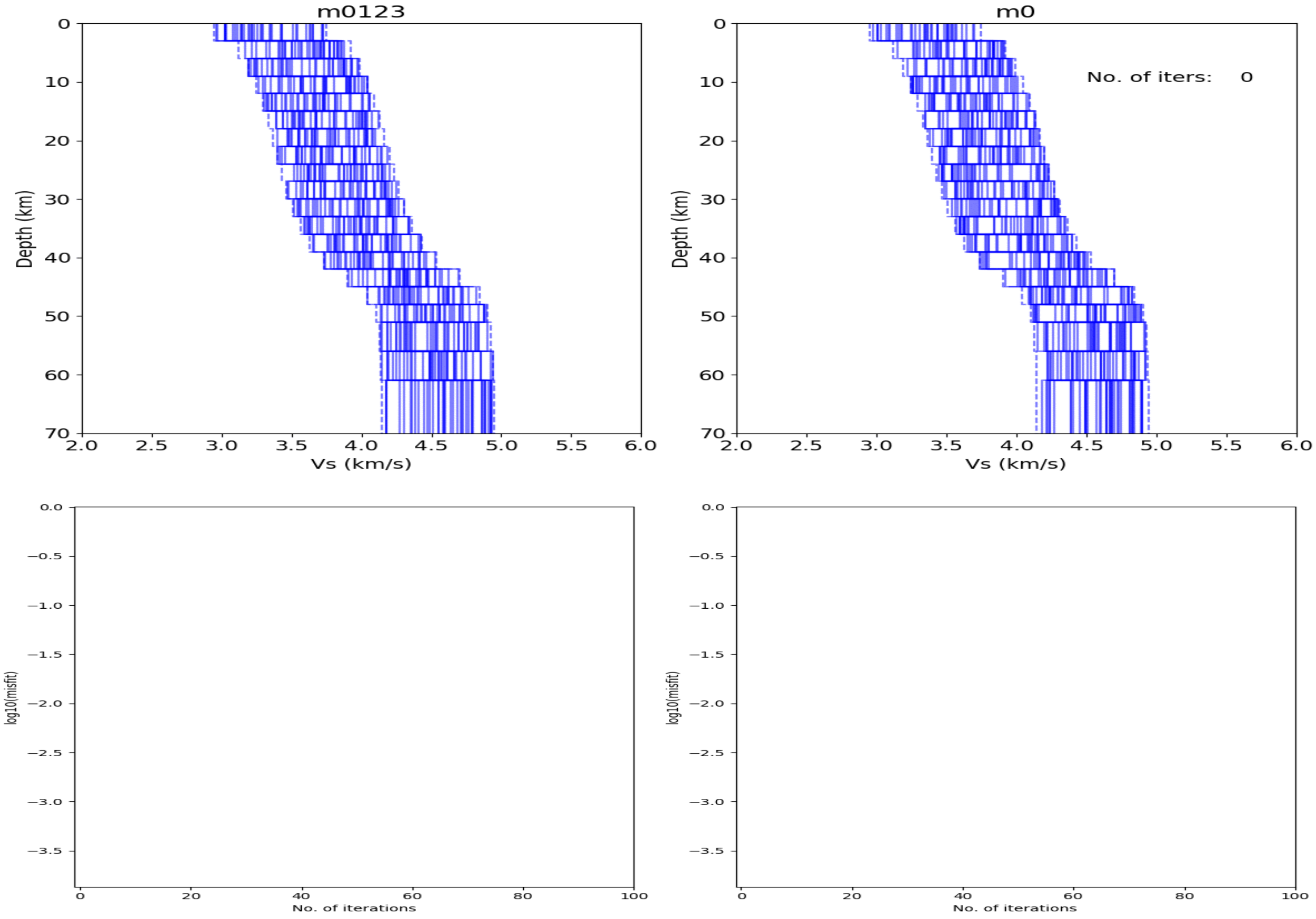


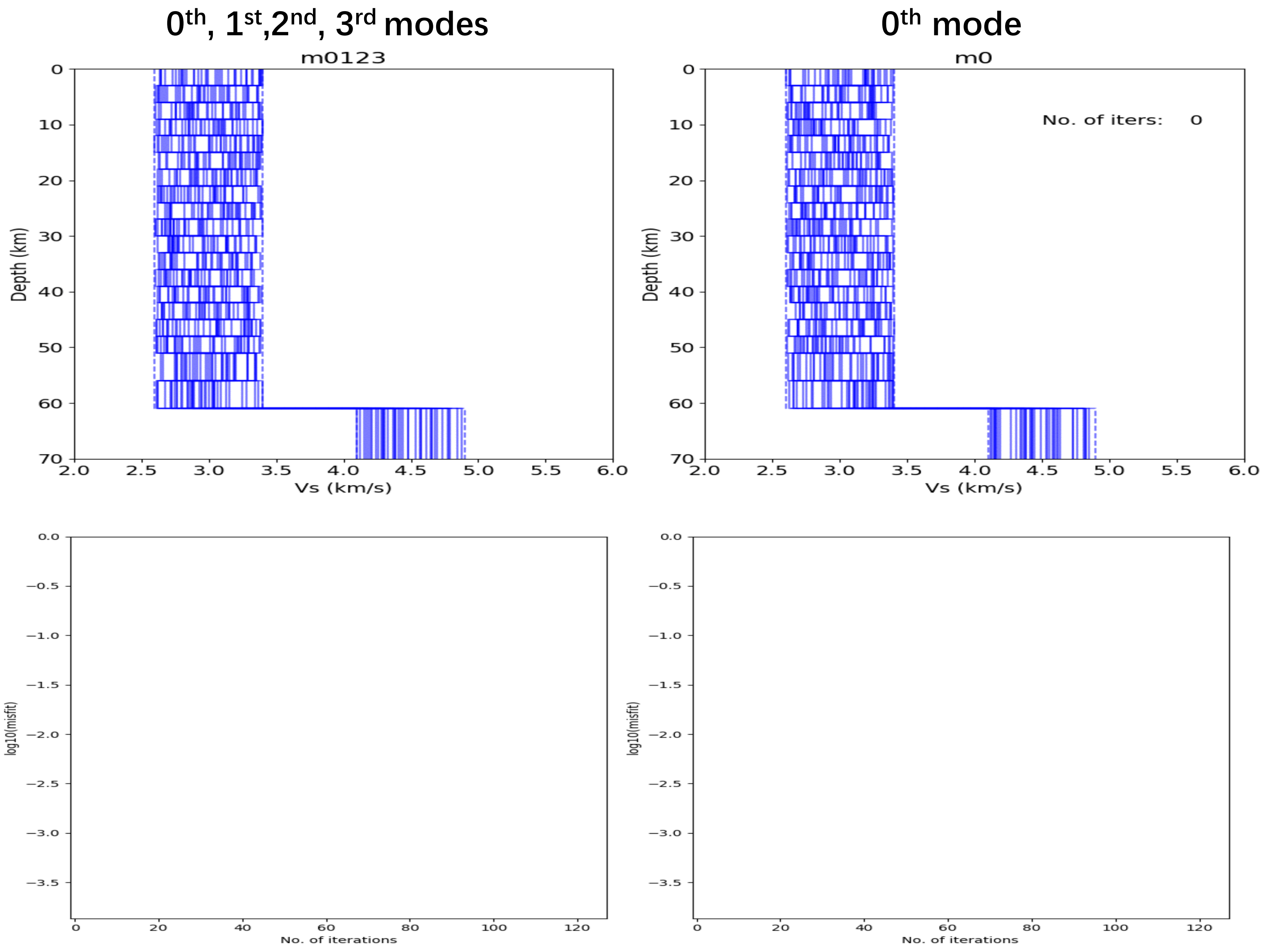
0^{th}, 1^{st}, 2^{nd}, 3^{rd} modes

0^{th} mode

Model iteration of 40 random initial models

Convergency of objective functions for 40 runs

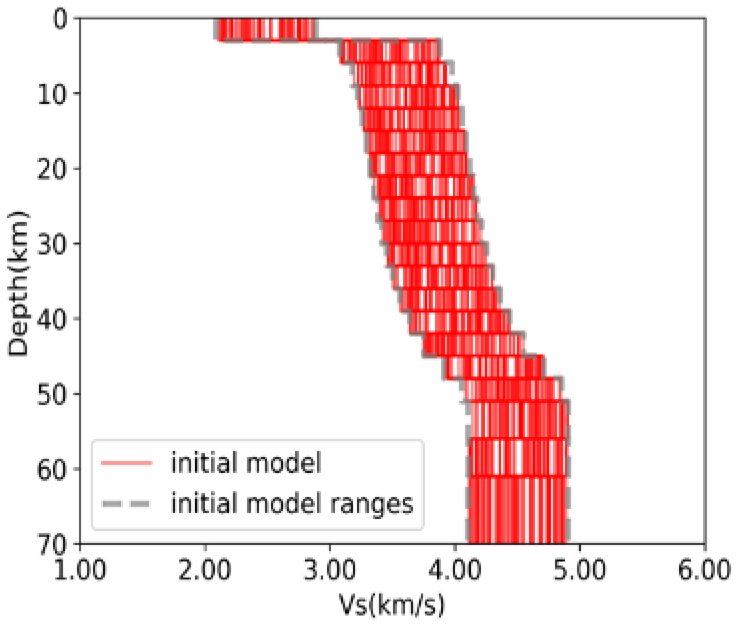


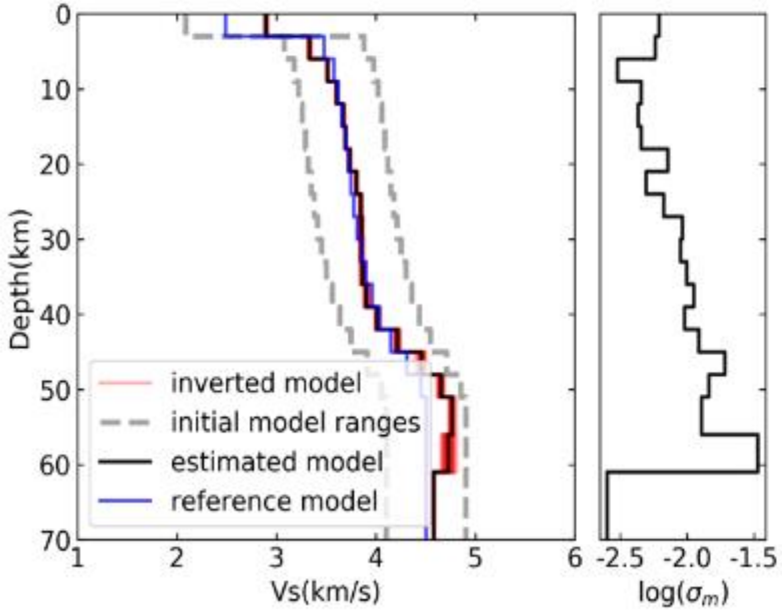


Model iteration of 40 random initial models

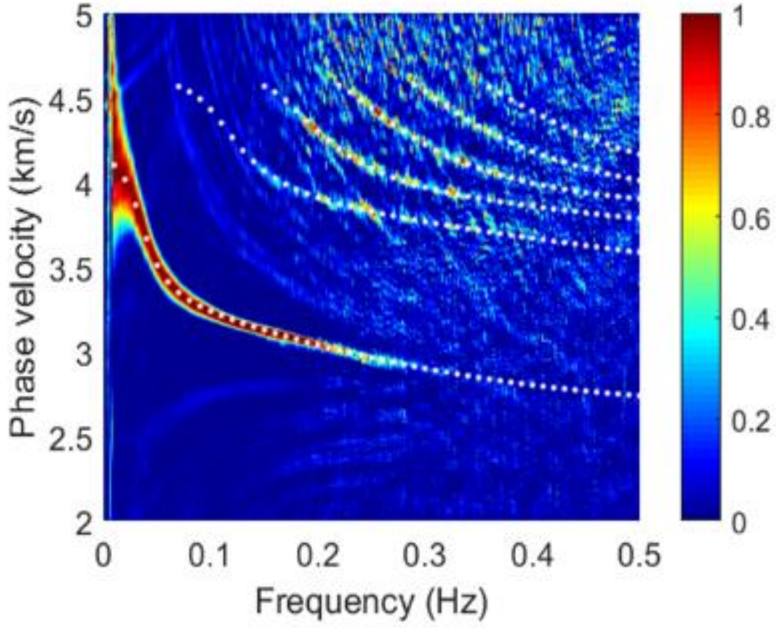
Convergency of objective functions for 40 runs

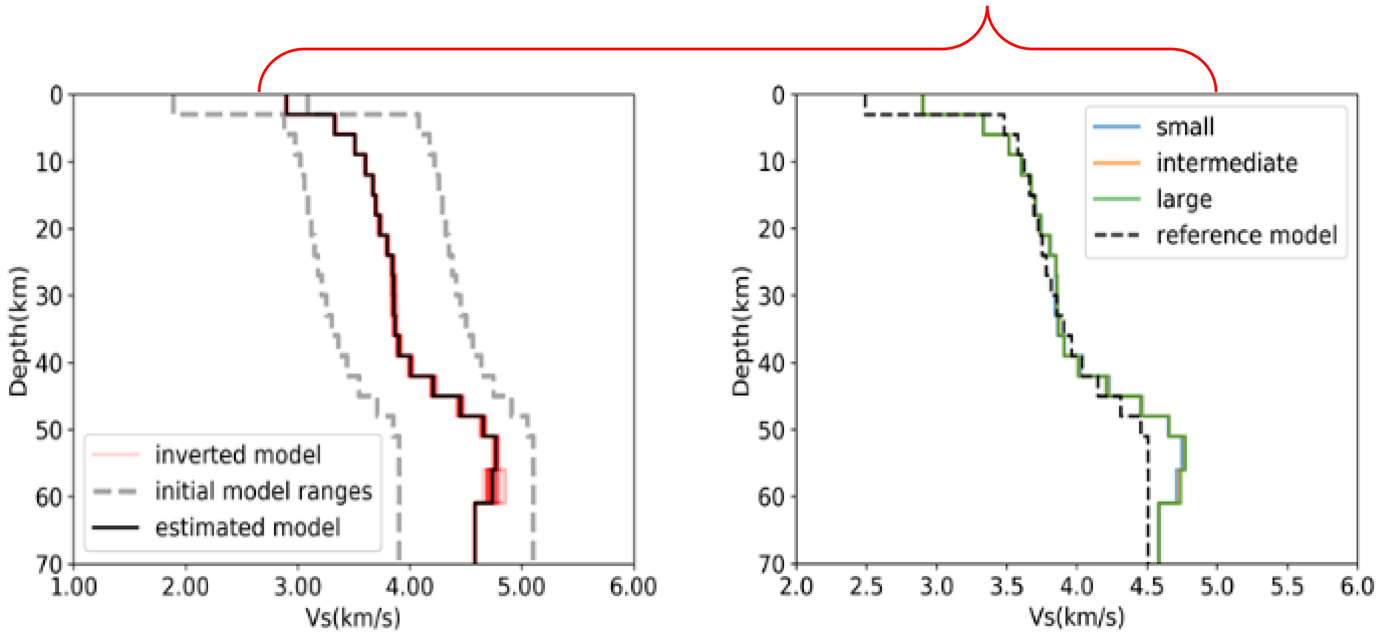
Inversion Results for Midwestern US





反演后的拟合





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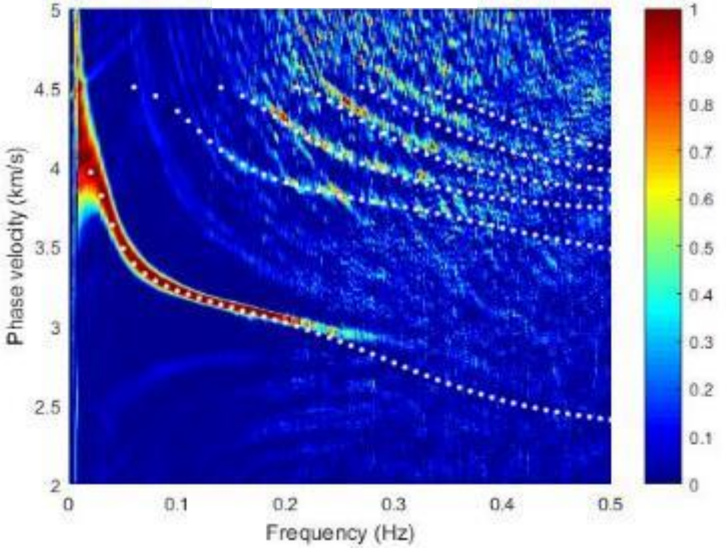
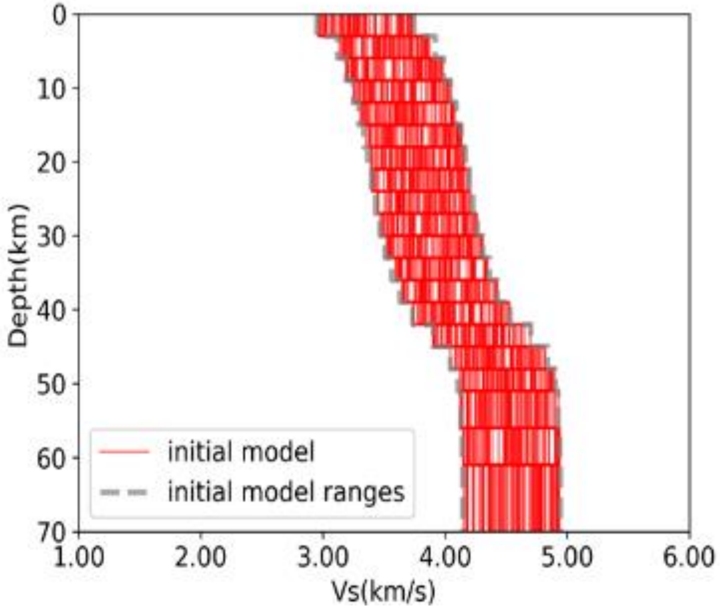
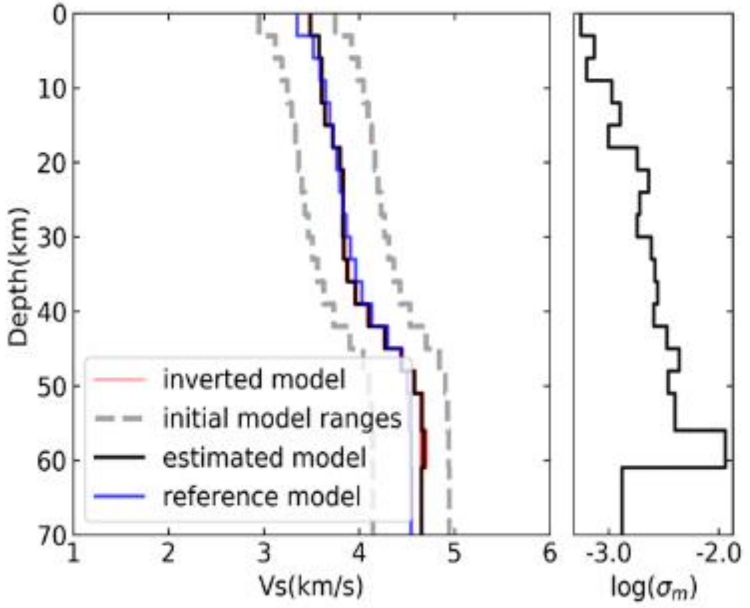
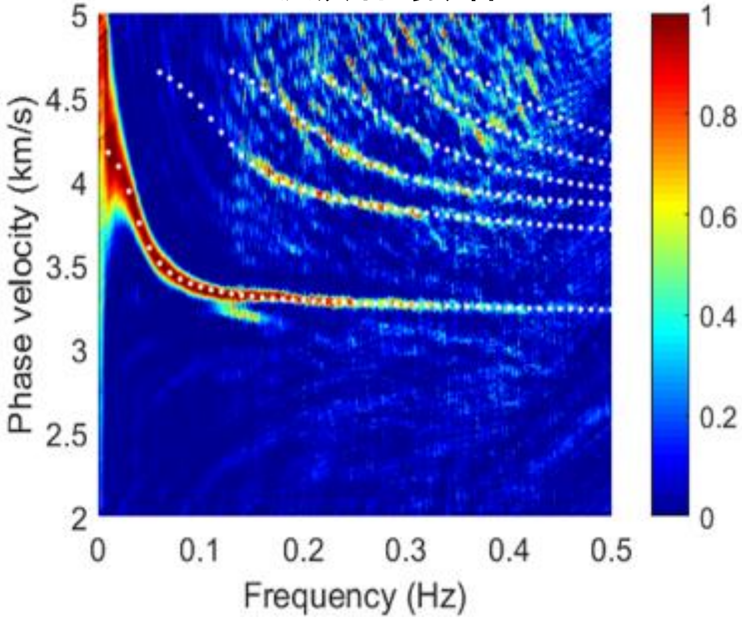


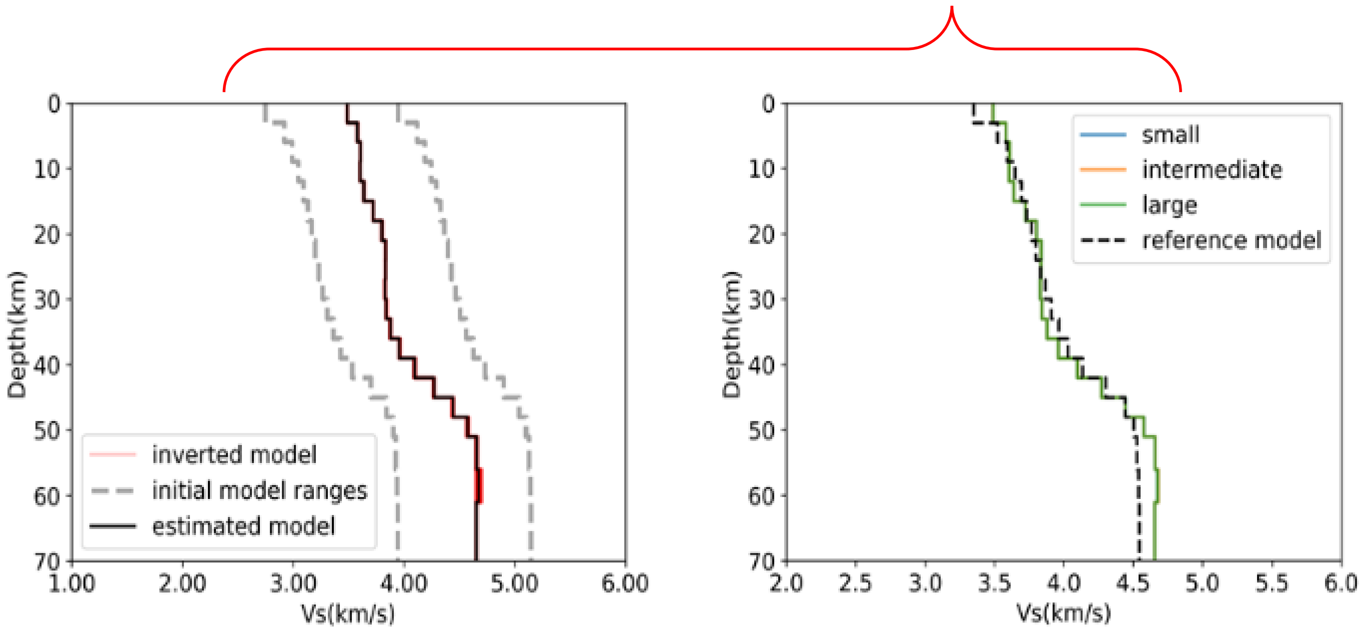
Inversion Results for Northeastern US



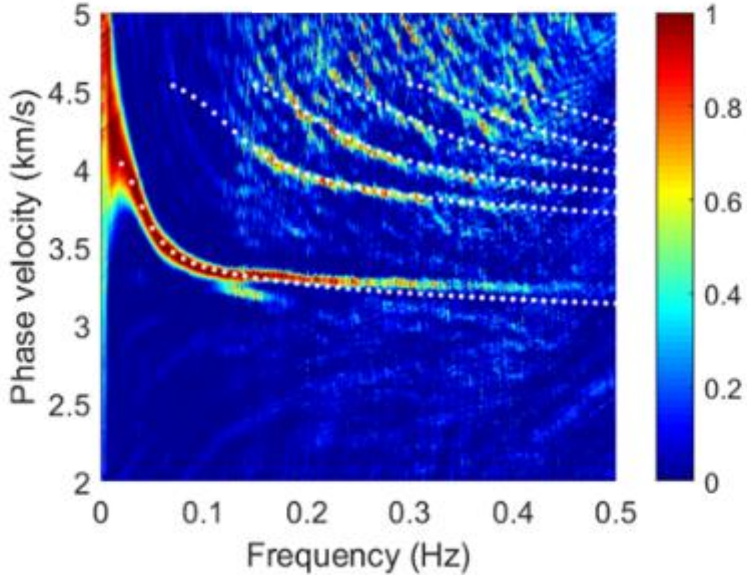


反演后的拟合

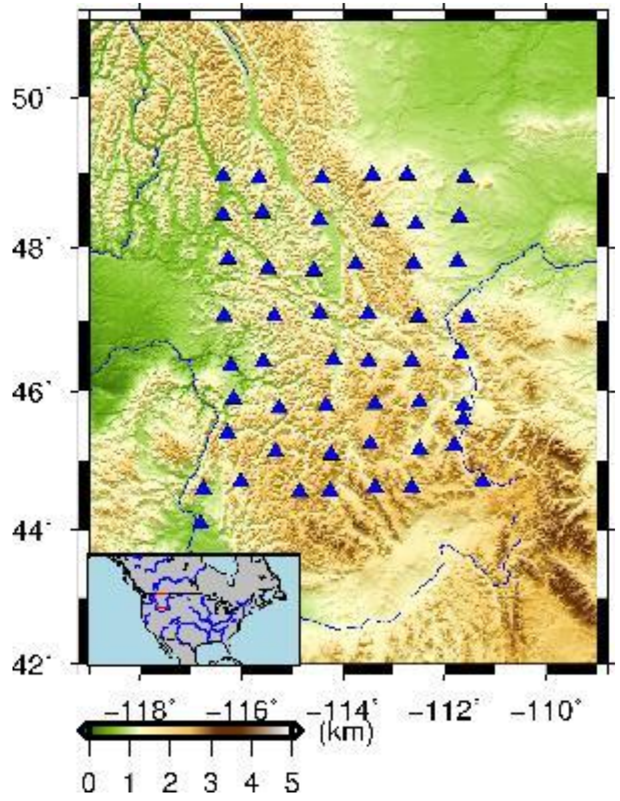




反演前的拟合



Inversion Results：Northwestern US



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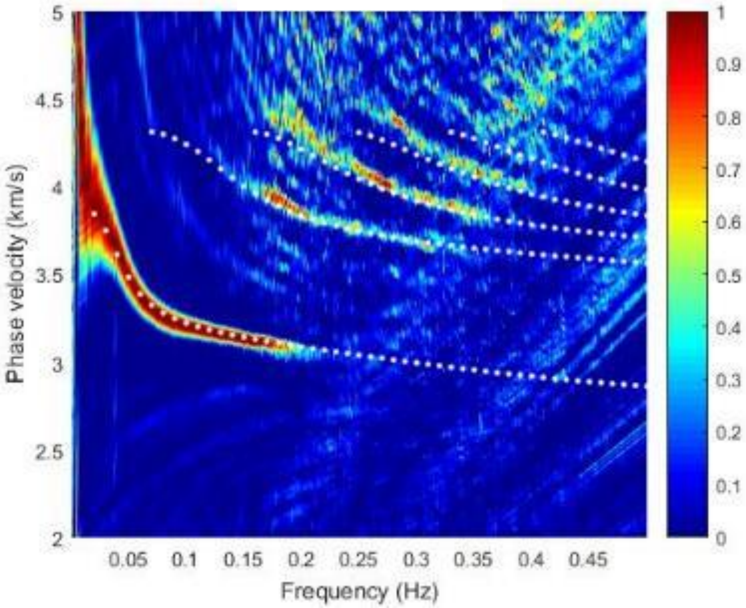
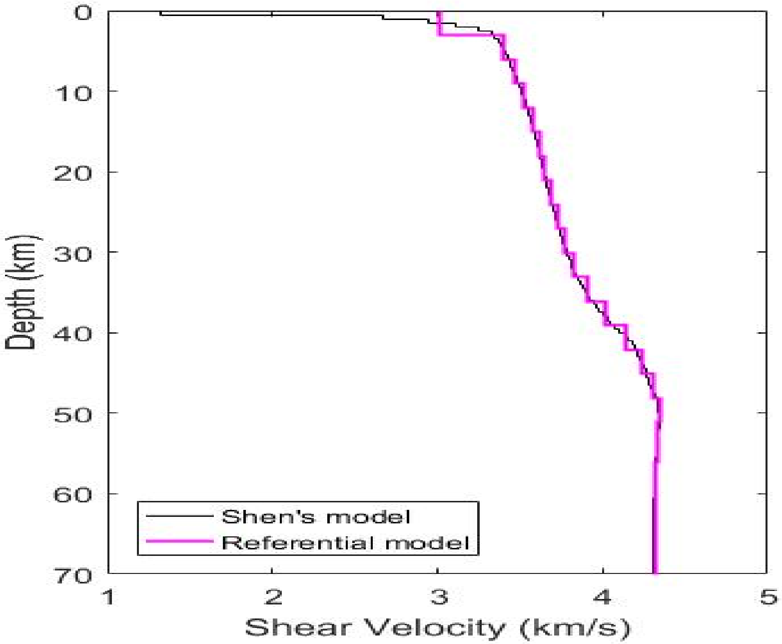
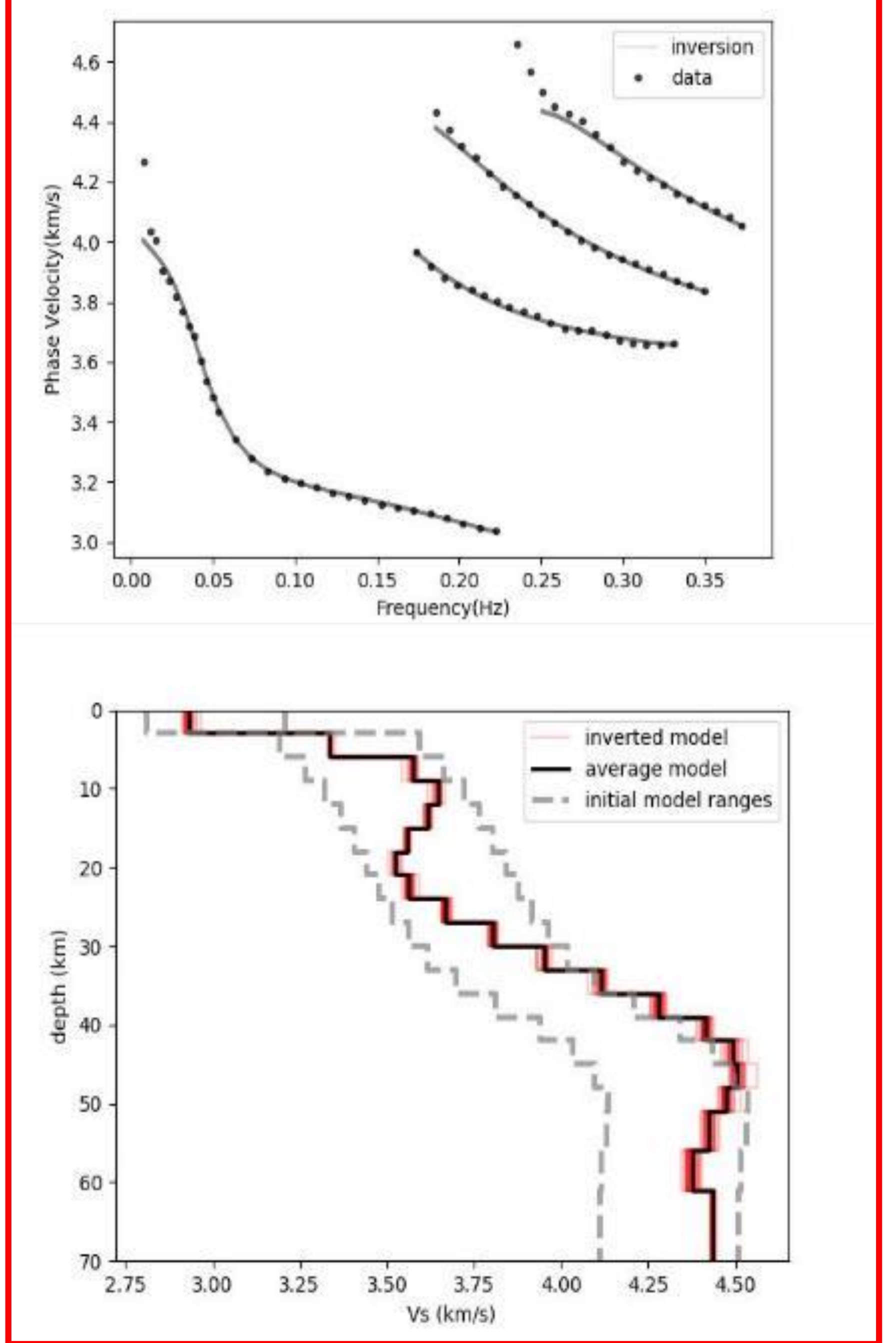
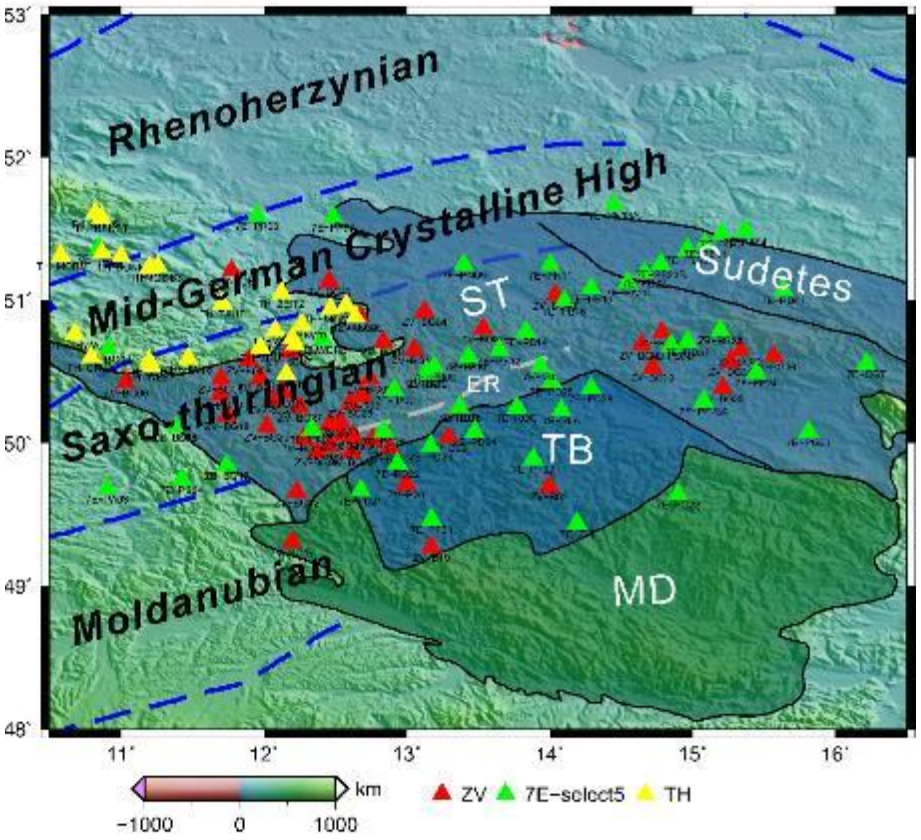




反演结果



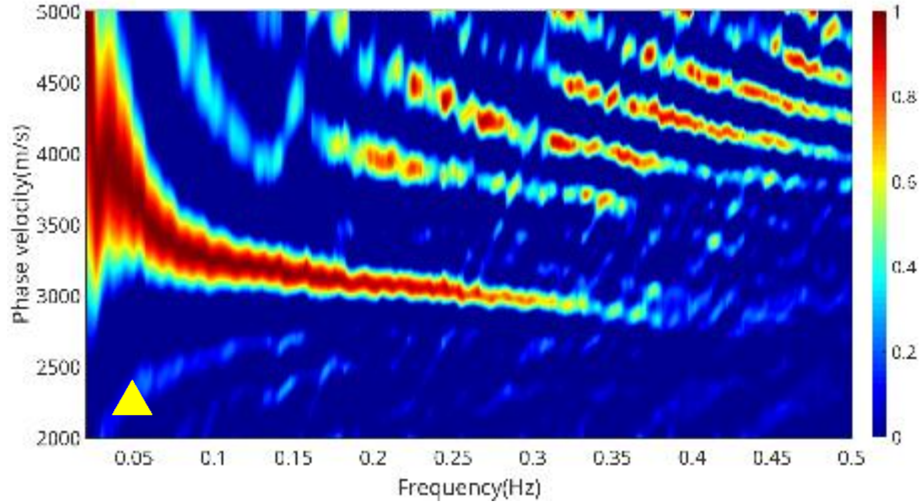
Northwest of Bohemian Massif

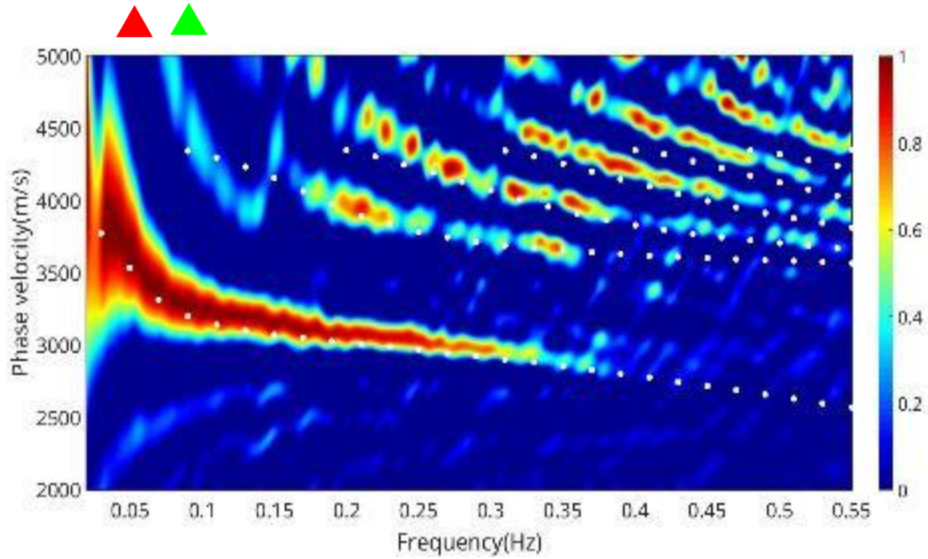


2001.1-2005.12

2017.1-2017.12

2007.1-2007.12





ST: Saxo-thuringian of Bohemian Massif

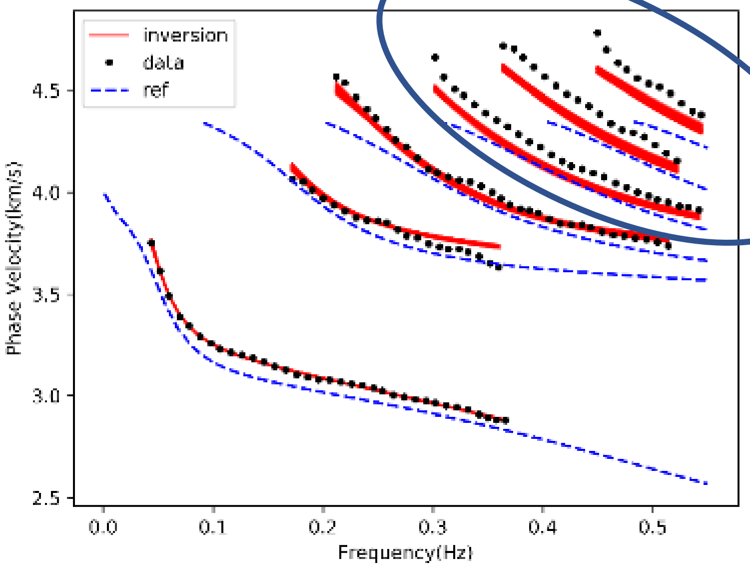
TB Tepla-Barrandian of Bohemian Massif

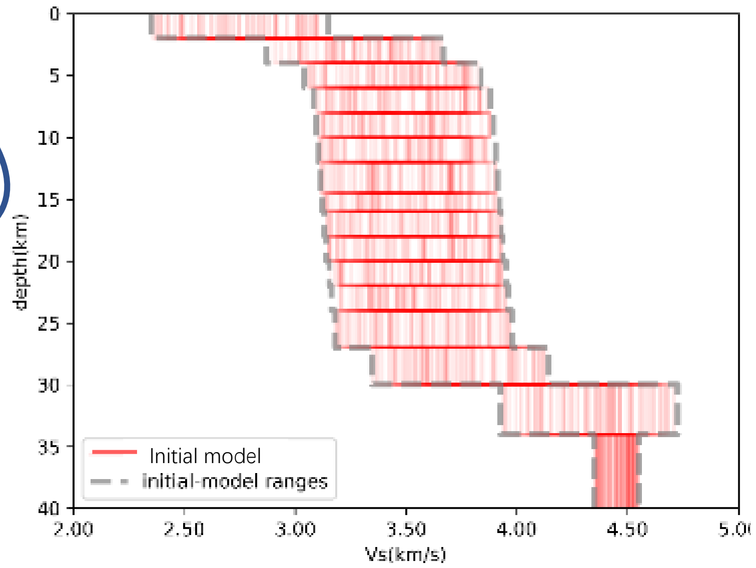
MD: Moldanubian of Bohemian Massif

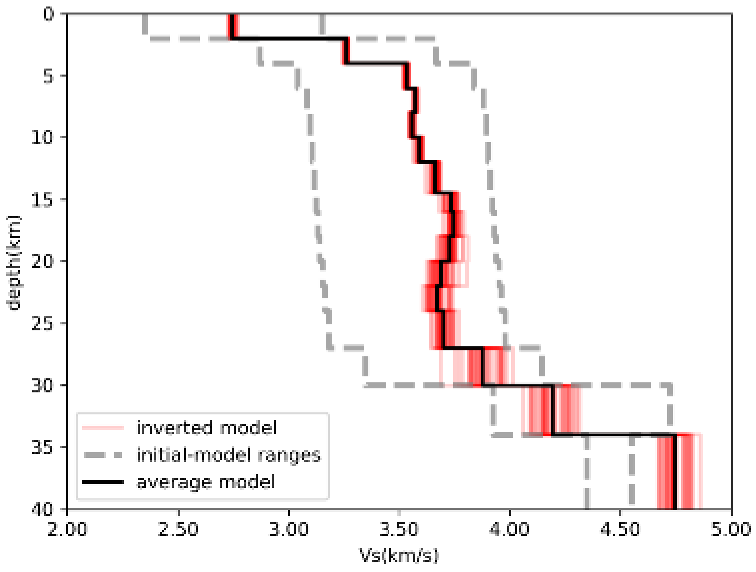
ER: Eger Rift

(Data from IRIS)

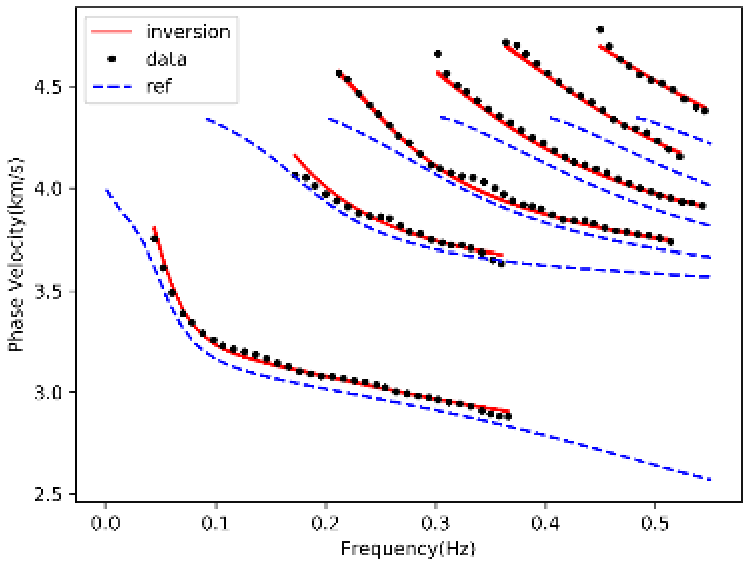
- **Only fundamental mode for Vs inversion**

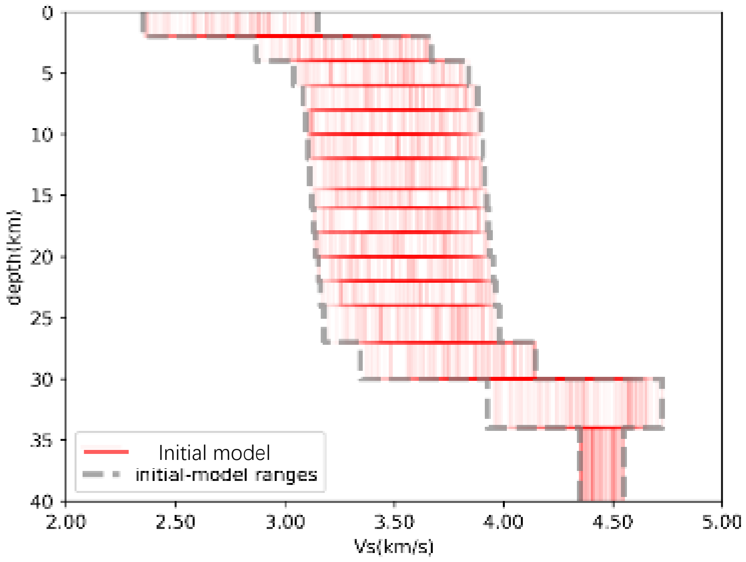


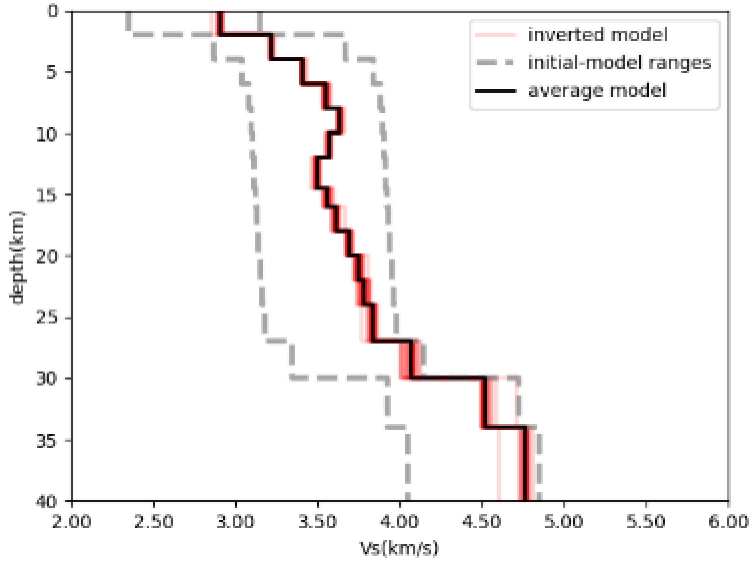


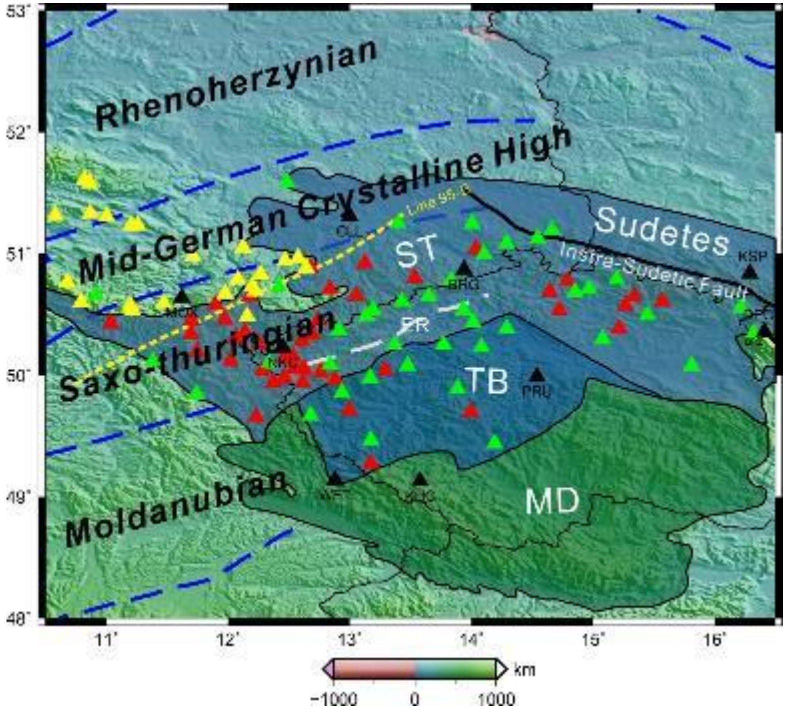


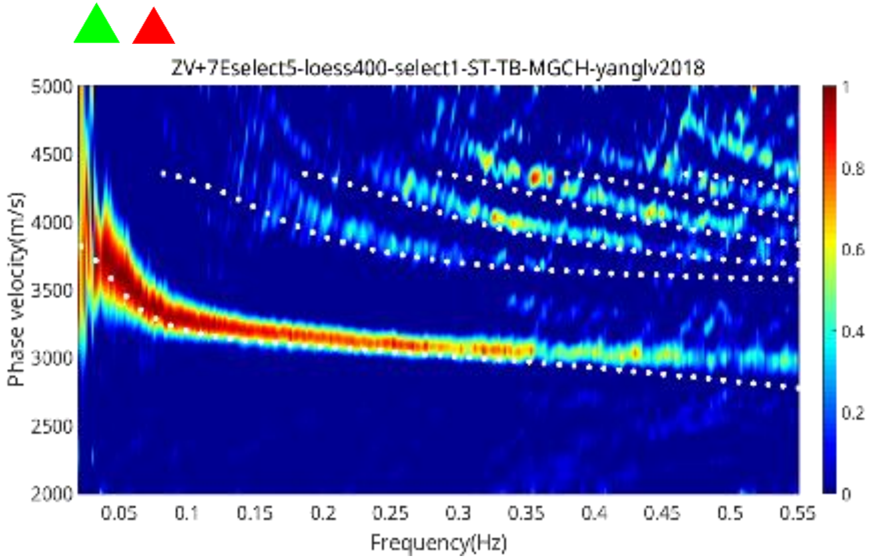
- **Both fundamental mode and Higher modes for Vs inversion**



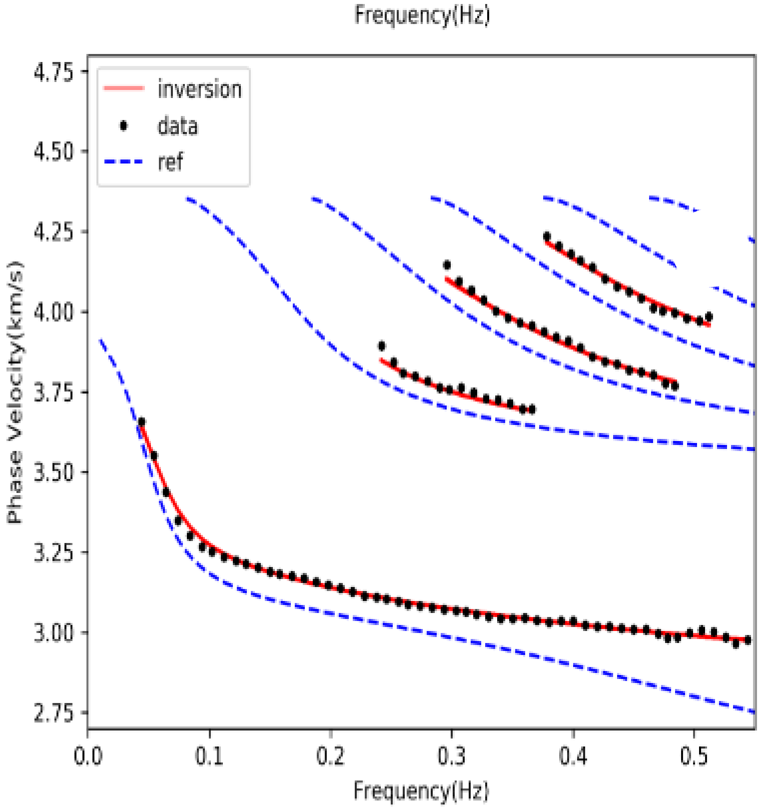


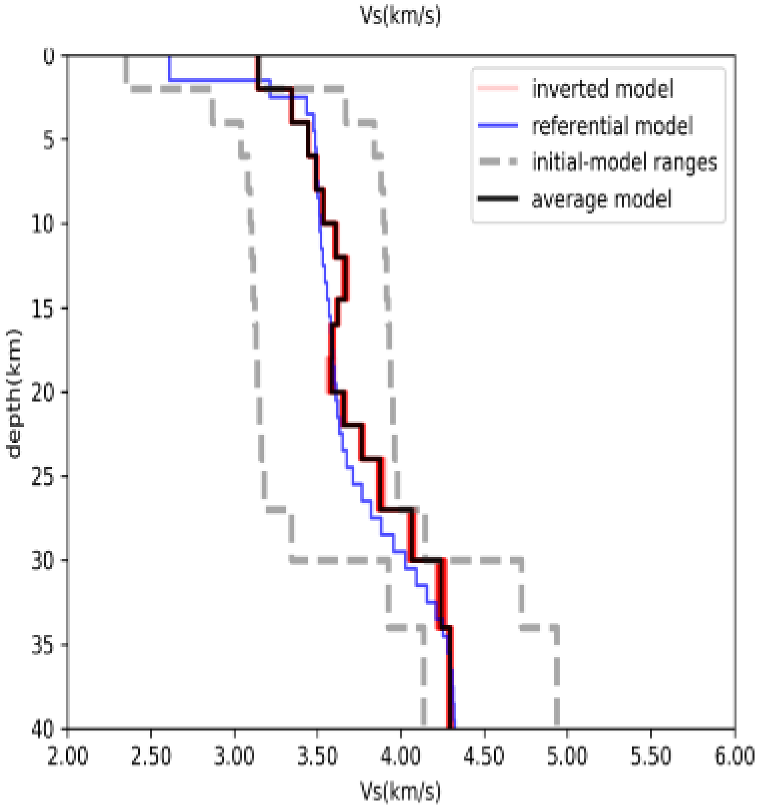



Rhenoherzynian
Mid-German Crystalline High
Sudetes
Intra-Sudetic Fault
ST
TB
MD
Saxo-thuringian
Moldanubian
km
-1000
0
1000


ZV+7Eselect5-loess400-select1-ST-TB-MGCH-yanglv2018
Phase velocity(m/s)
Frequency(Hz)

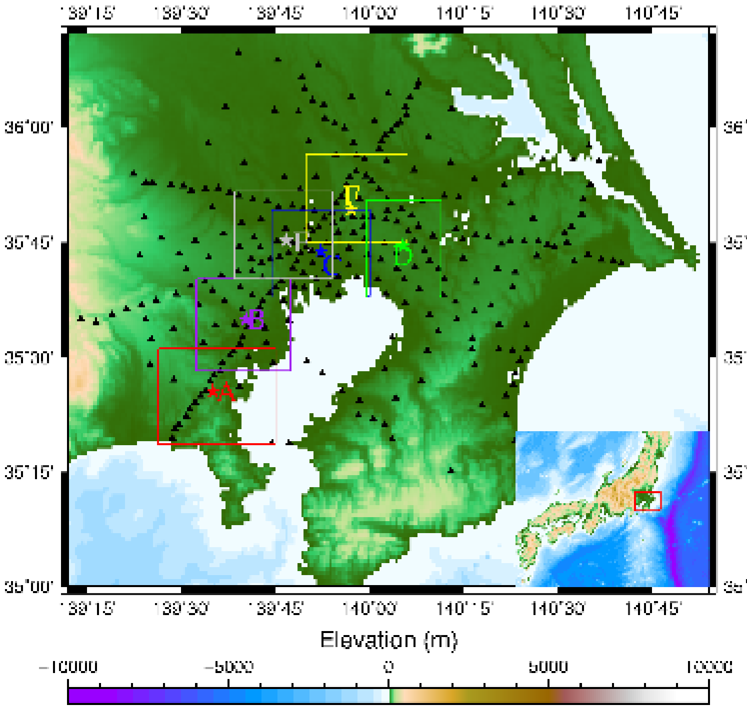
反演结果


Frequency(Hz)
inversion
data
ref
Phase Velocity(km/s)
Frequency(Hz)

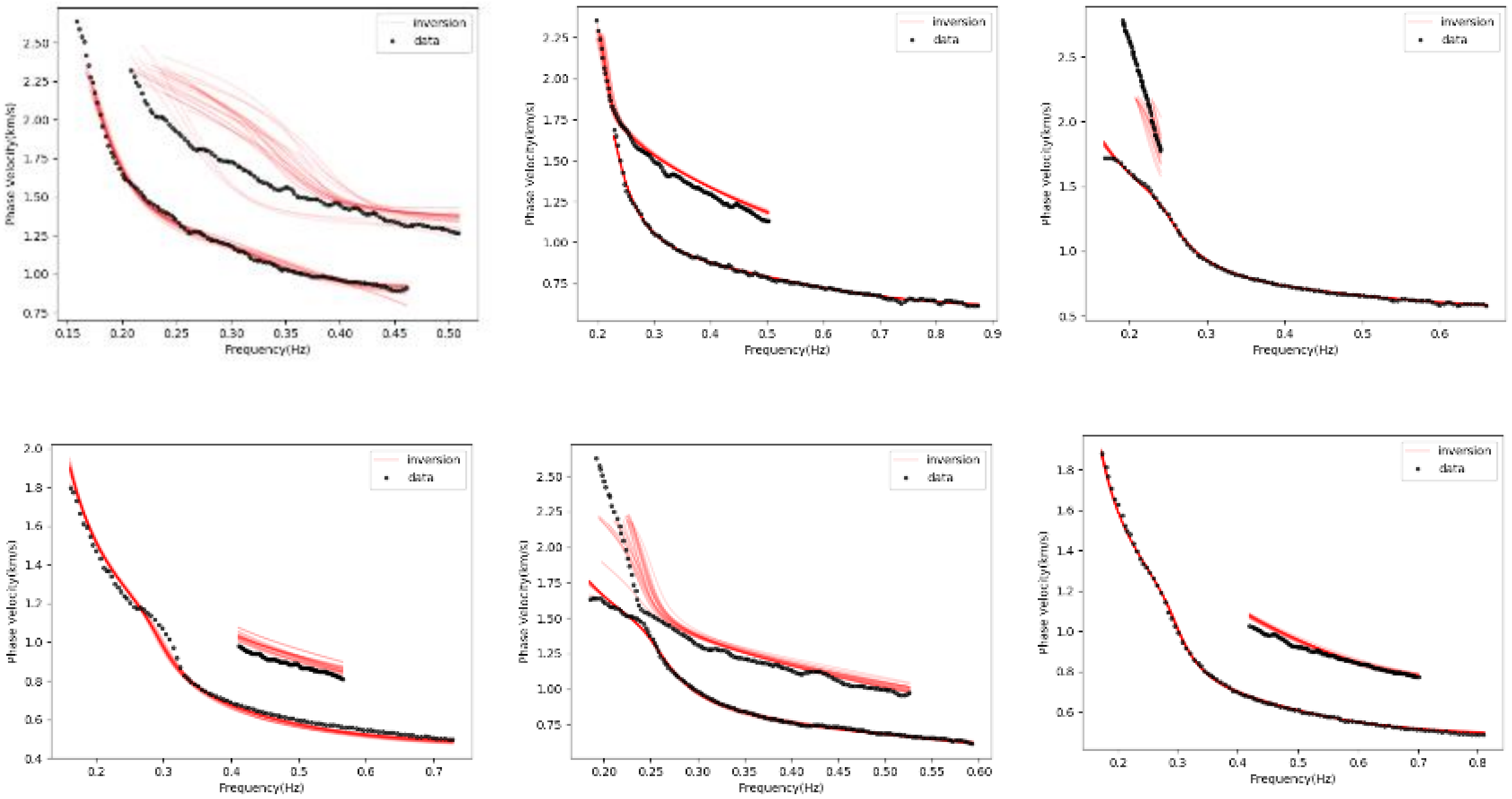

Vs(km/s)
inverted model
referential model
initial-model ranges
average model
depth(km)
Vs(km/s)

Inversion Results of Kanto Basin

--Results for 0th modal dispersion curve



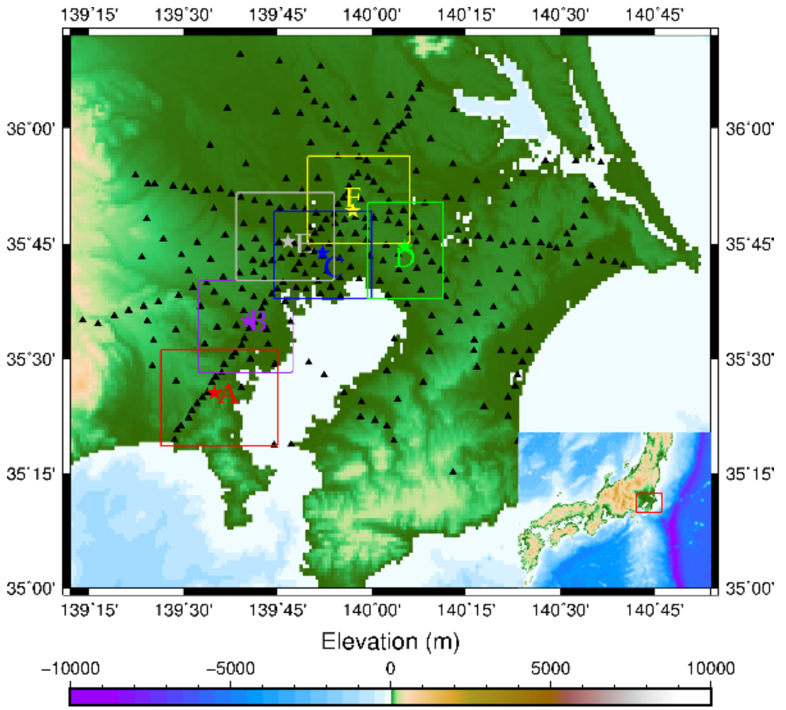
Fitting of 0th modal dispersion curve only

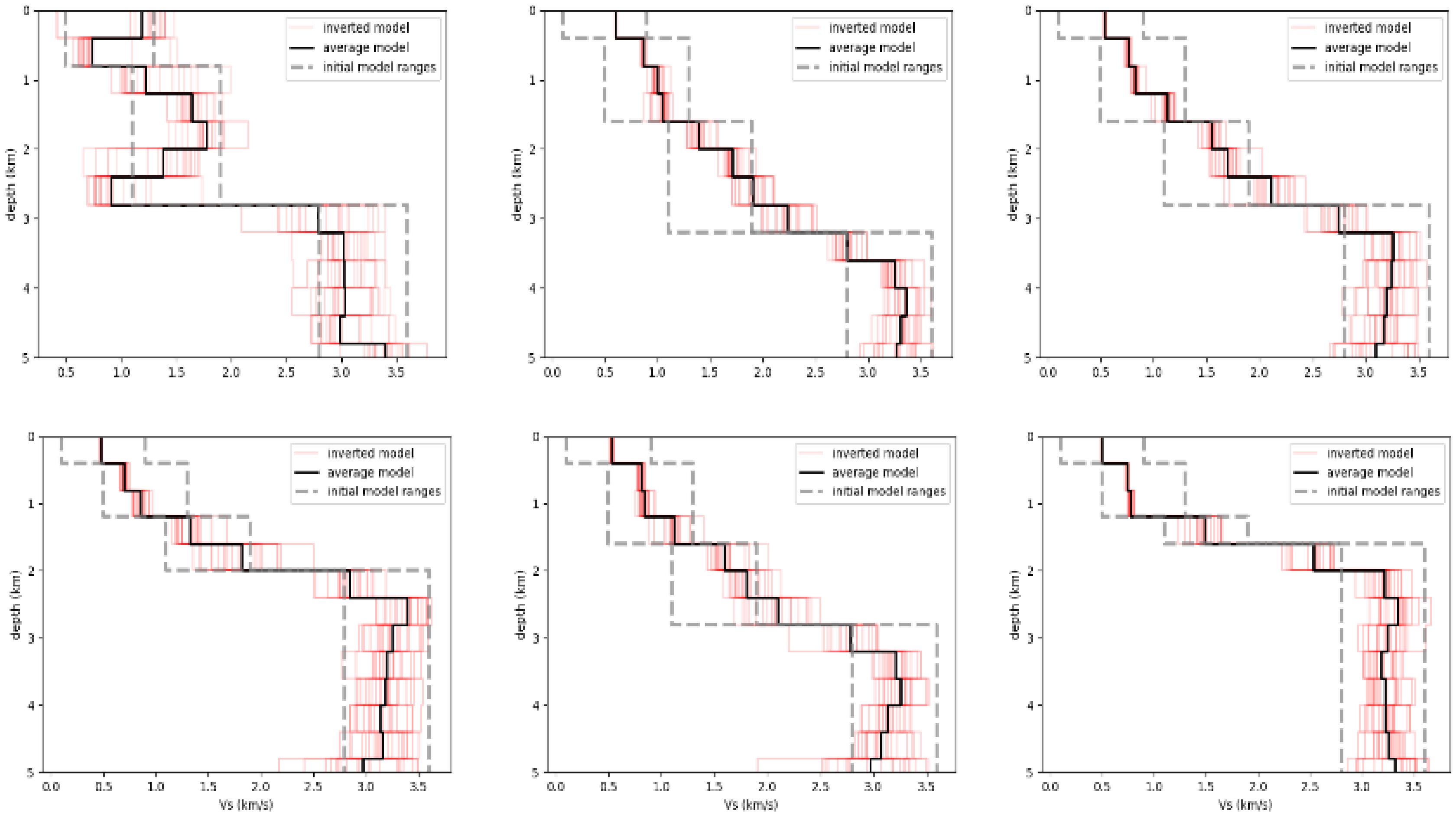


Inversion Results of Kanto Basin

--Results for 0th modal dispersion curve

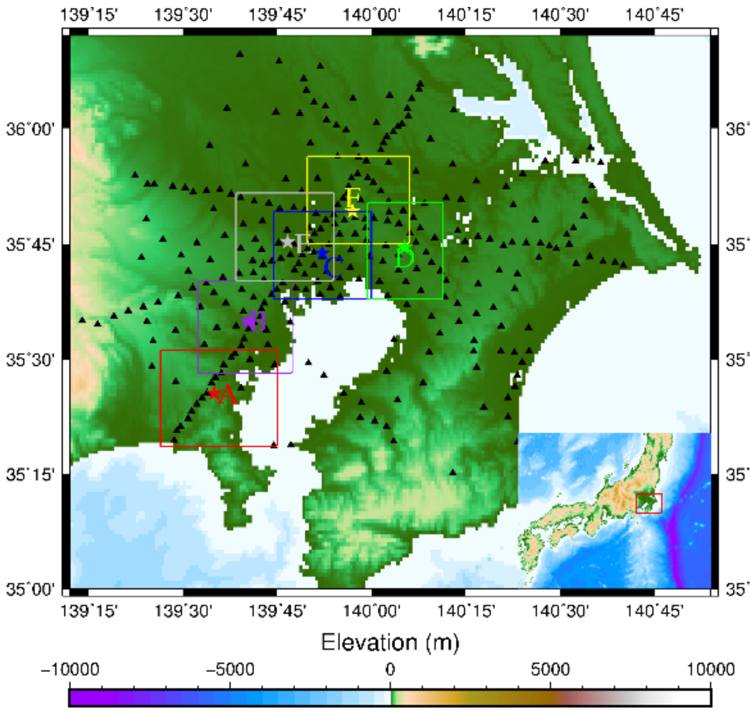
Results of 0th modal dispersion curve only



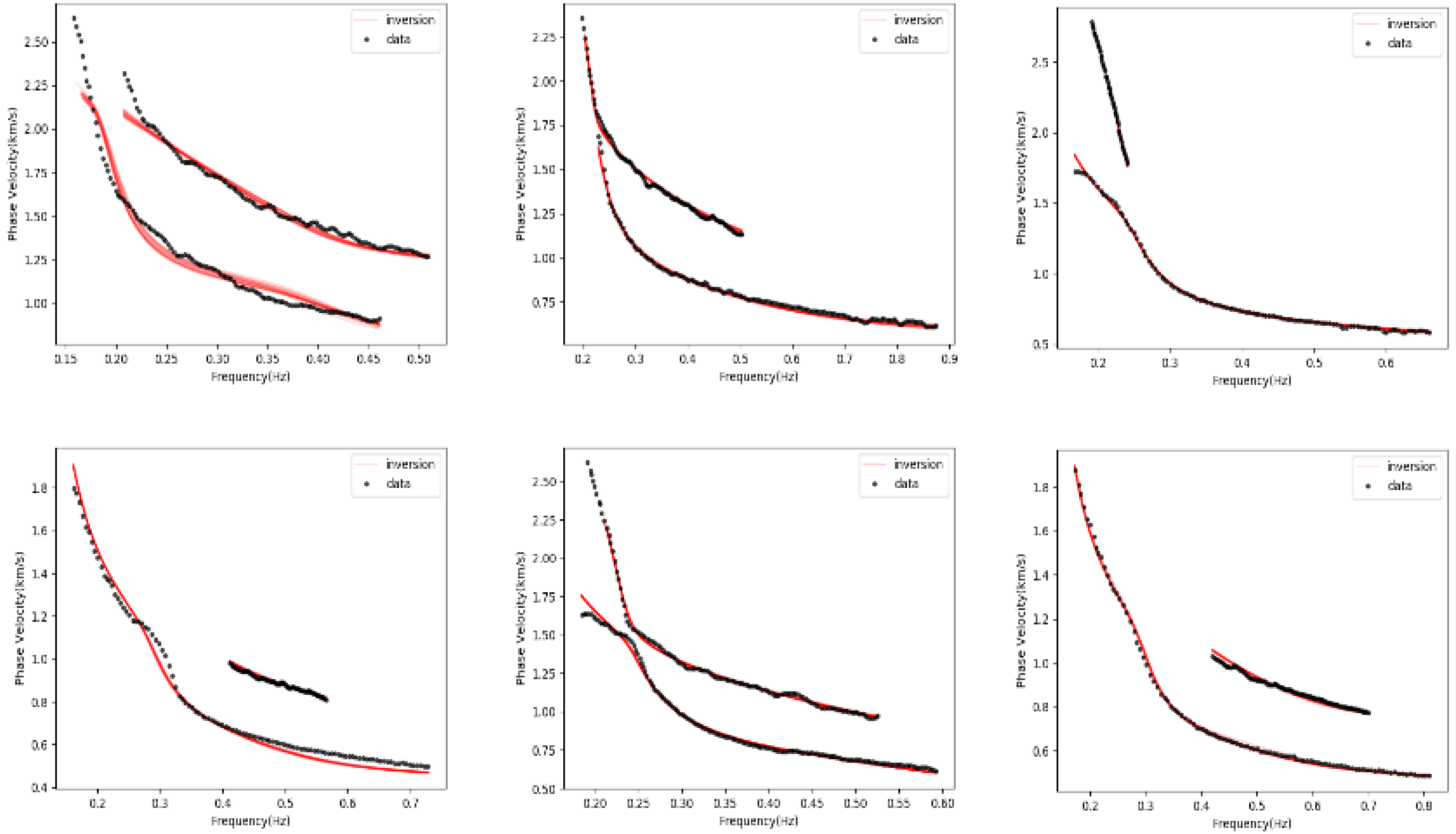


Inversion Results of Kanto Basin

--Results for $0^{th}+1^{st}$ modal dispersion curves

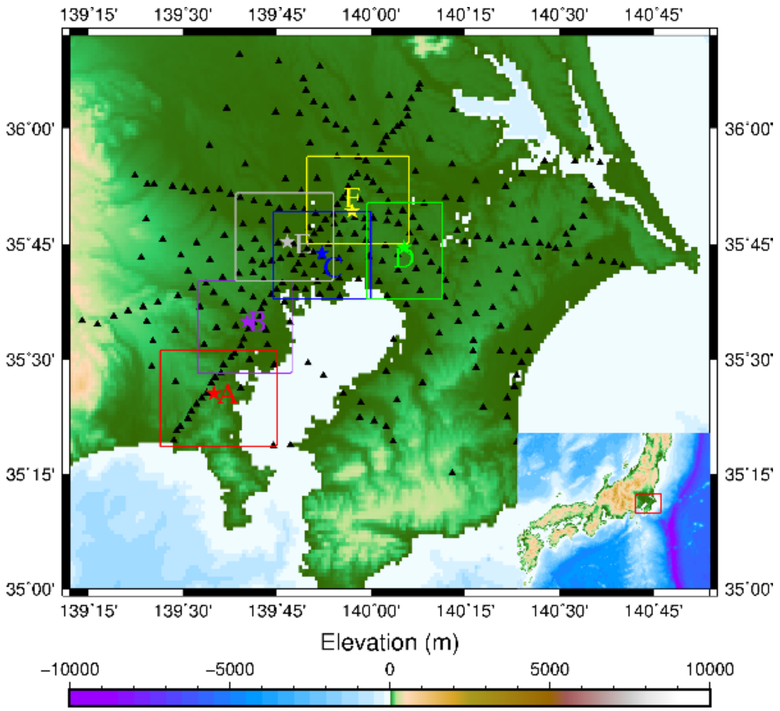


Fitting of $0^{th}+1^{st}$ modal dispersion curves

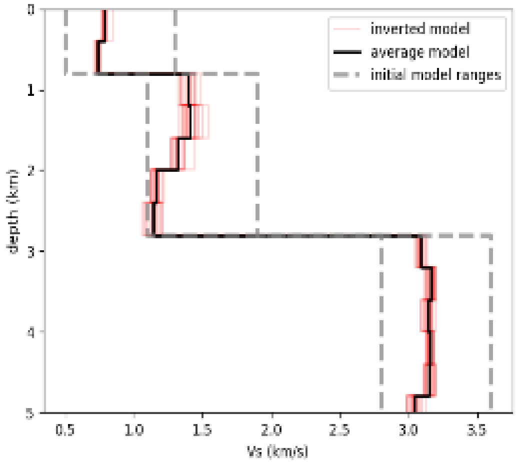


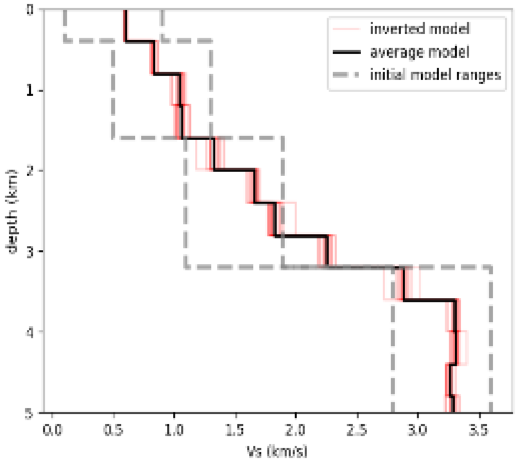
Inversion Results of Kanto Basin

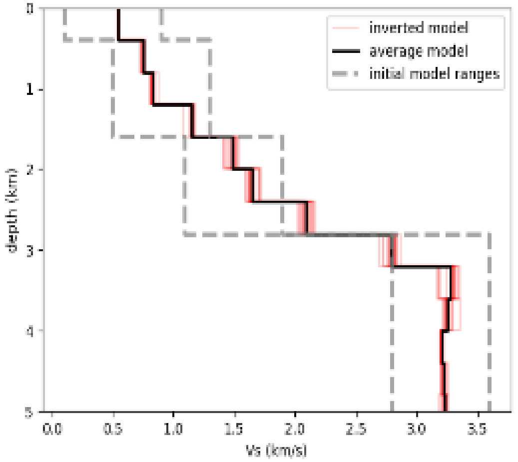
--Results for $0^{th}+1^{st}$ modal dispersion curves

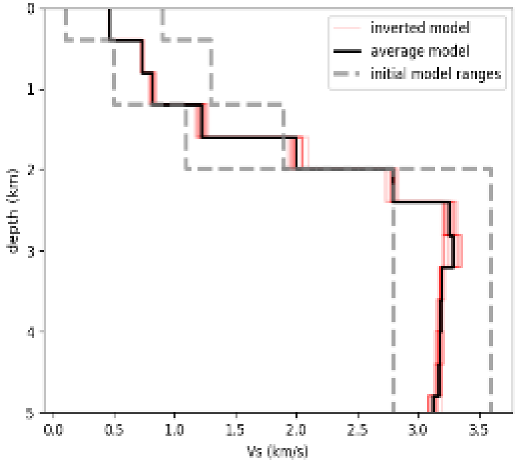


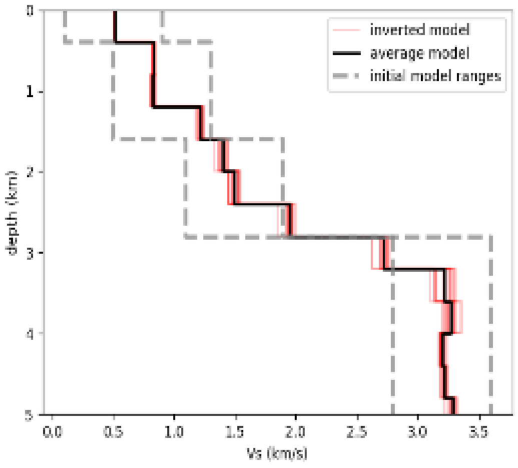
Results of $0^{th}+1^{st}$ modal dispersion curves

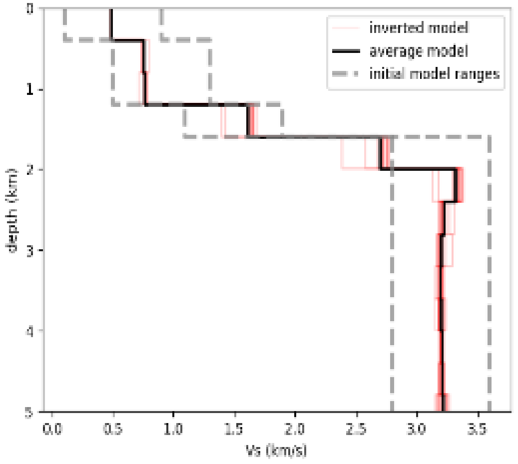






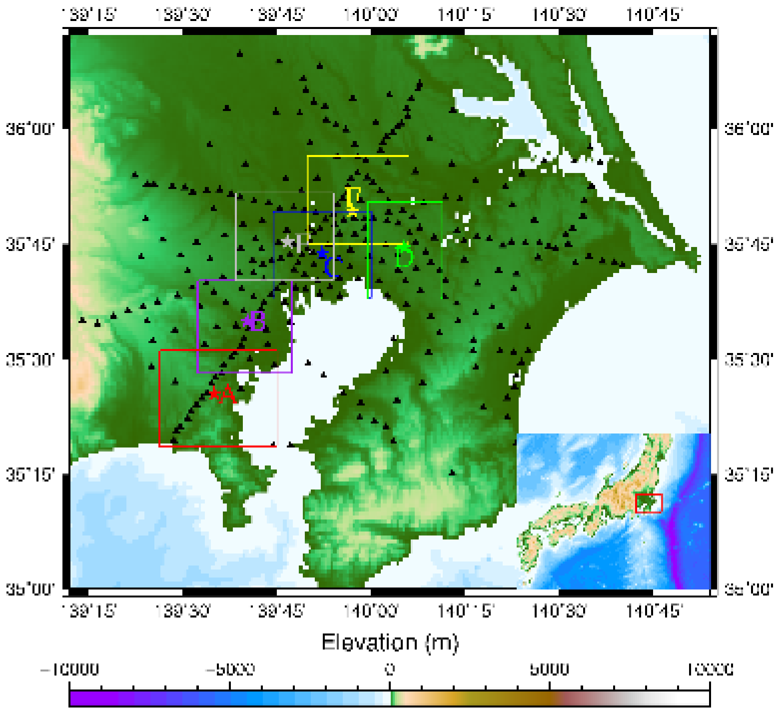


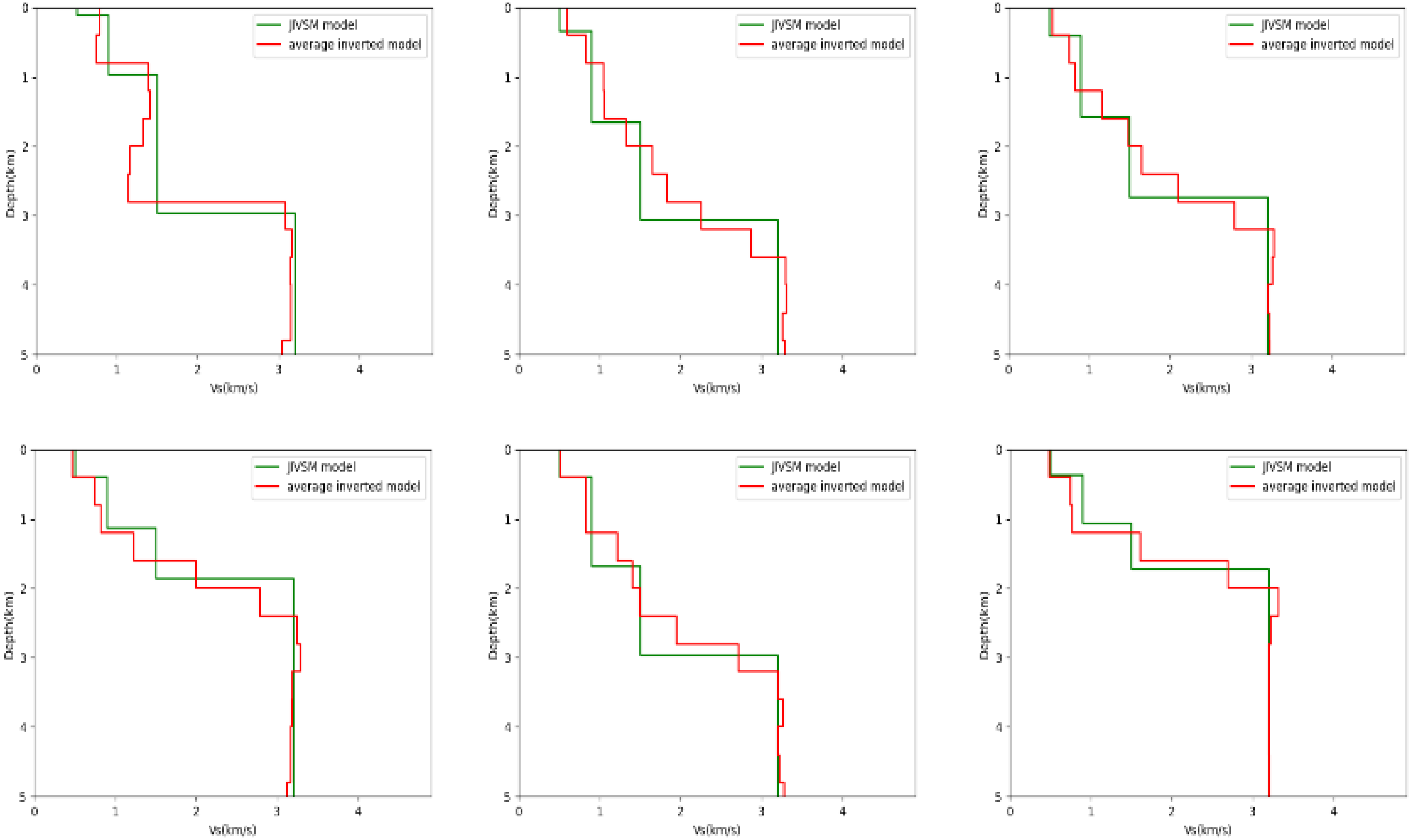




Inversion Results of Kanto Basin

Comparisons with previous model





Outlines

- Importance of higher modes for SWTM, as well as ambient seismic noise tomography
- How to extract the dispersion curves of higher mode from ambient seismic noise?
- How do the higher modes improve the inversion?
- Brief introduction of F-J method

Innovative method：

Frequency-Bessel Transform Method

(F-J method)

AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2018JB016595

Key Points:
- We proposed a new method (the F-J method) to image dispersion curves of overtones of Rayleigh waves from ambient seismic noise data
- Preliminary applications to USArray

Frequency-Bessel Transform Method for Effective Imaging of Higher-Mode Rayleigh Dispersion Curves From Ambient Seismic Noise Data

Jiannan Wang[1], Gaoxiong Wu[1,2], and Xiaofei Chen[2]

[1]School of Geophysics, School of Earth and Space Sciences, University of Science and Technology of China, Hefei,

Wang, J., Wu, G., & Chen, X. (2019). Frequency-Bessel transform method for effective imaging of higher-mode Rayleigh dispersion curves from ambient seismic noise data. *Journal of Geophysical Research: Solid Earth*, *124*. https://doi.org/10.1029/2018JB016595

ambient seismic noise data. *Journal of Geophysical Research: Solid Earth*, *124*.
https://doi.org/10.1029/2018JB016595

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1. Introduction

Ambient seismic noise, which is also called microtremor in the field of geotechnique engineering, is a stochastic wavefield generated by various passive sources (e.g., Okada & Suto, 2003; Yang et al., 2007; Yang & Ritzwoller, 2008). After the pioneering works of Aki (1957) and other researchers (e.g., Campillo & Paul, 2003; Derode et al., 2003; Lobkis & Weaver, 2001; Sabra et al., 2005a, 2005b; Sánchez-Sesma et al., 2011; Shapiro & Campillo, 2004; Shapiro et al., 2005; Snieder, 2004), once useless ambient noise data were con-

Fundamentals of F-J Method：

$$C(r,\omega) = A \cdot Im\{G_{zz}(r, z=0; \omega)\}$$

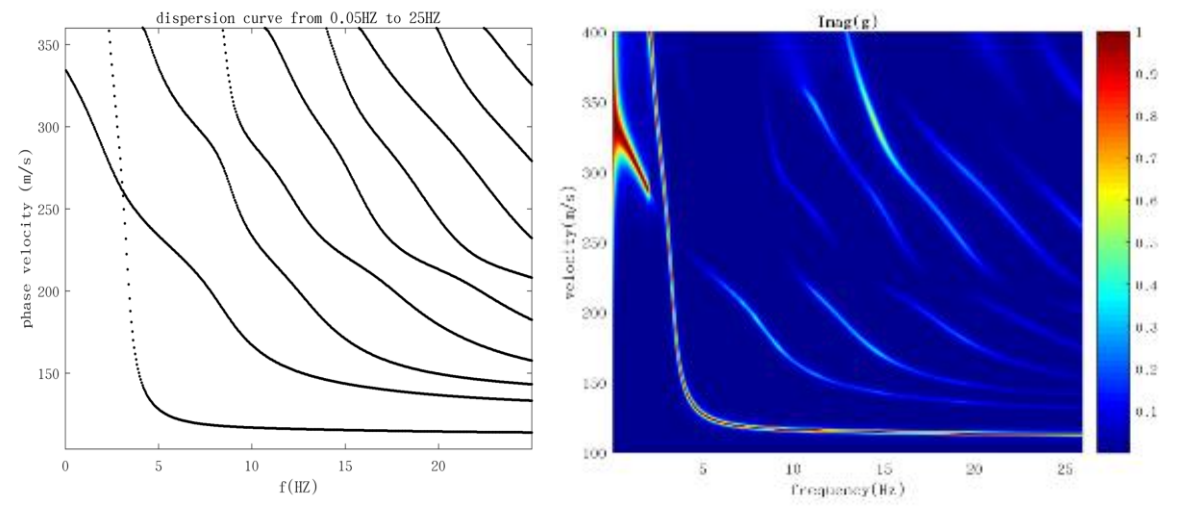
$$I(c,\omega) = \int_0^{+\infty} C(r,\omega) J_0\left(\frac{\omega}{c} r\right) r dr$$

$$G_{zz}(r, z; \omega) = \int_0^{+\infty} g(\omega, k, z) J_0(kr) k dk$$

$$\int_0^{+\infty} J_0\left(\frac{\omega}{c} r\right) J_0(kr) r dr = \frac{1}{k}\delta\left(k - \frac{\omega}{c}\right)$$

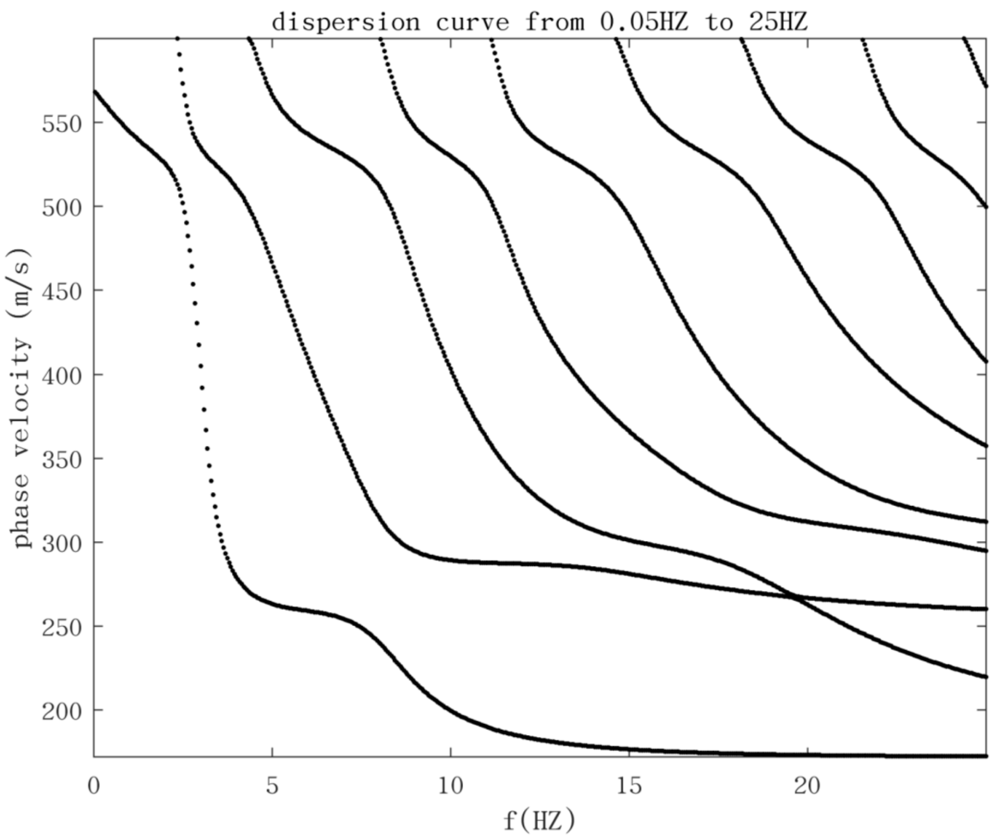
Measurable quality

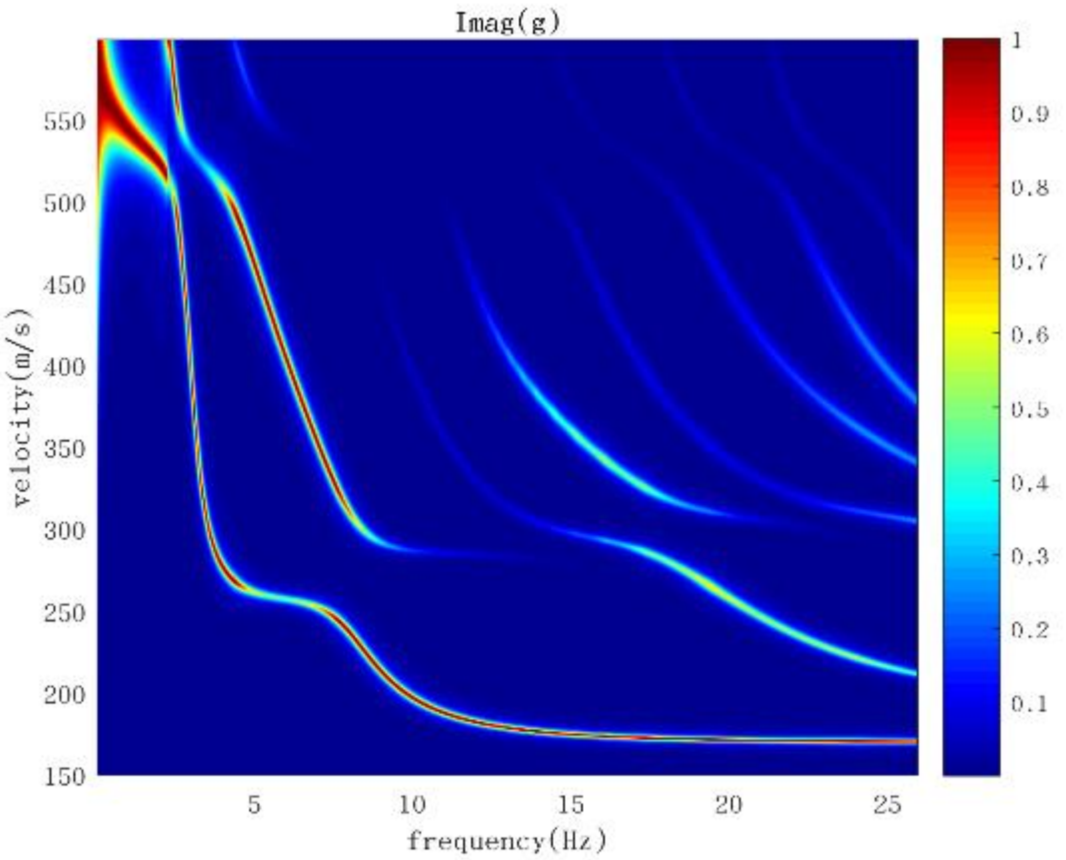
$$I(c,\omega) = A \cdot Im\left[g_z\left(\omega, \frac{\omega}{c}, 0\right)\right]$$



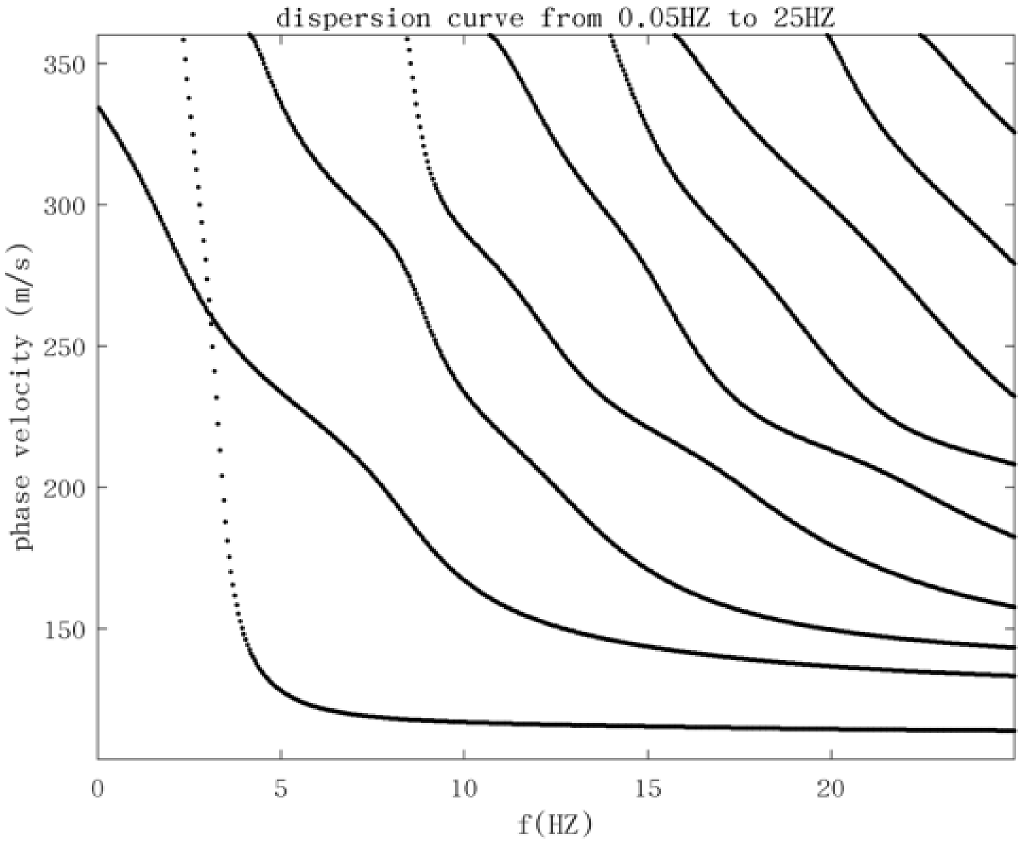
$$\begin{cases} Im\{g_z(z=0, c, \omega)\} \propto \frac{1}{S(c,\omega)} \\ S(c,\omega) = 0, \ when\ c = c_n(\omega), \\ \qquad n = 0,1,2, \ldots \end{cases}$$

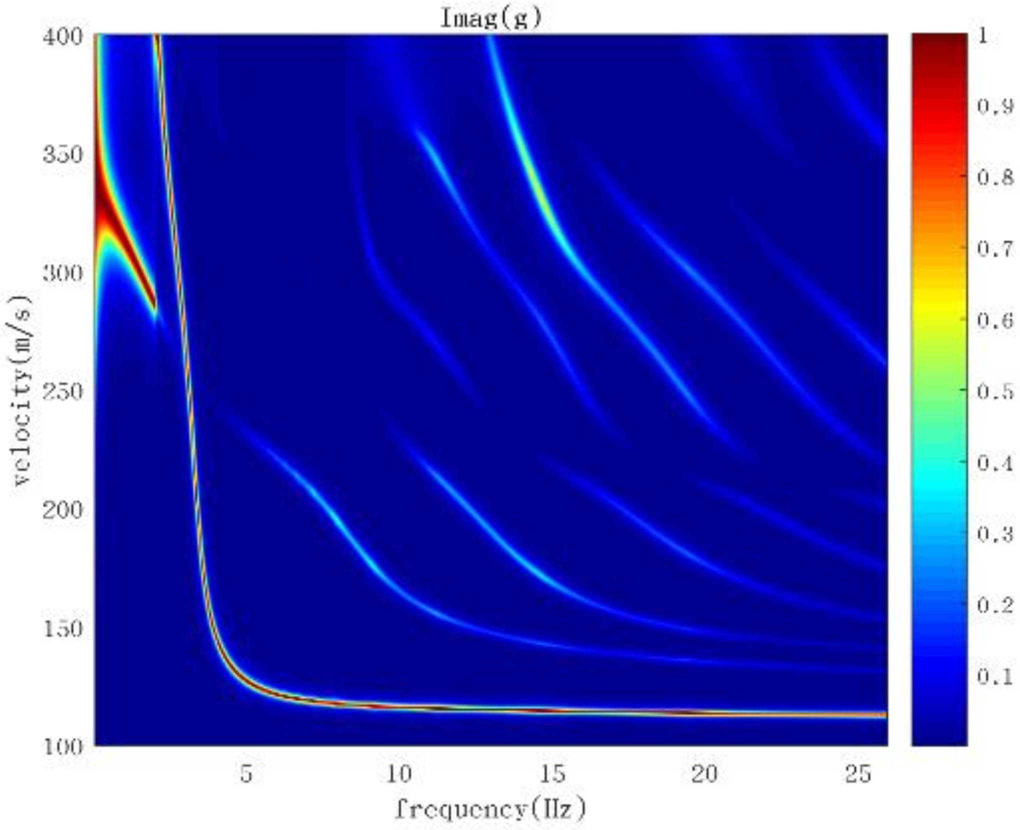
Properties of kernel $Im\{g_z(z=0,k,\omega)\}$:

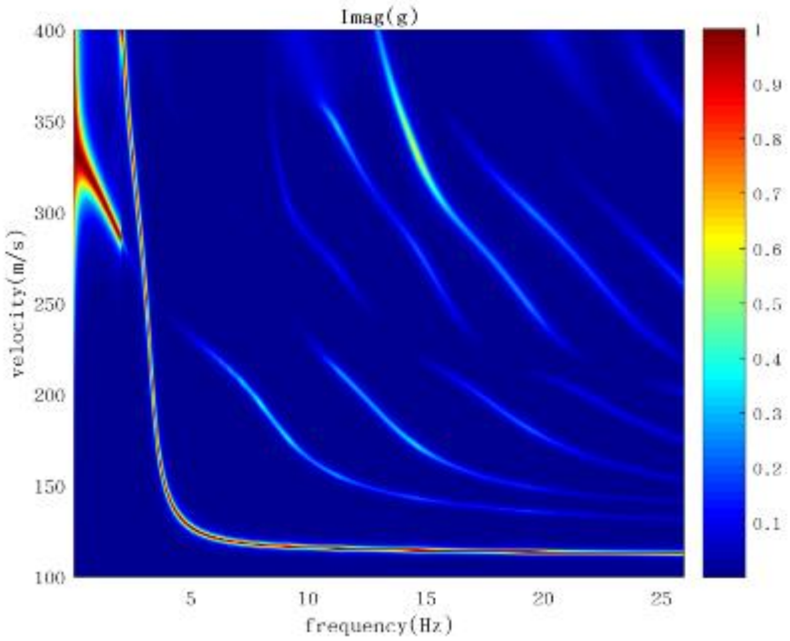


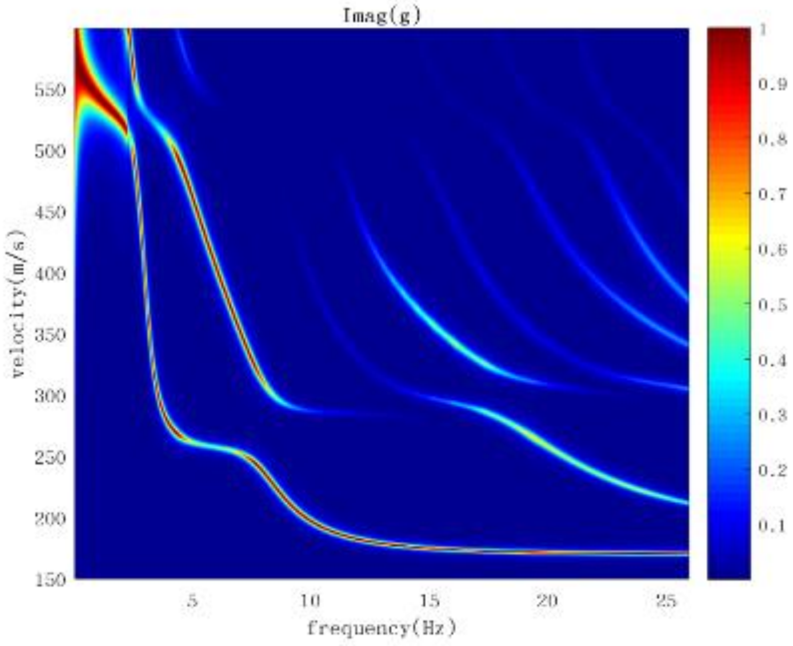


Properties of kernel $Im\{g_z(z=0,k,\omega)\}$:



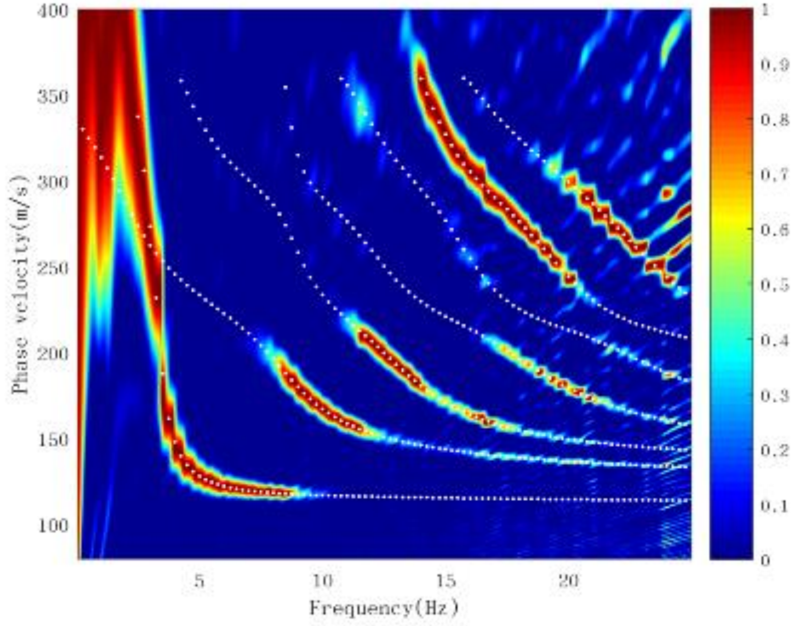


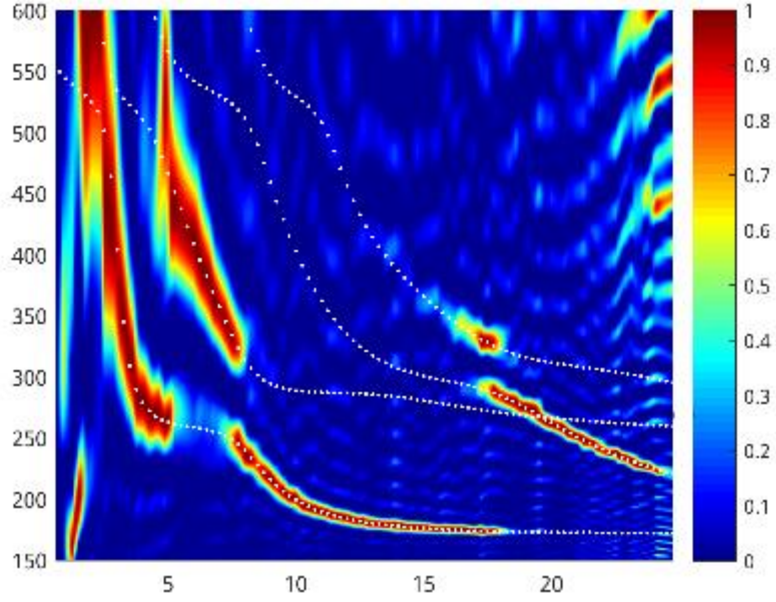




Calculated kernel

$$Im\{g_z(z=0,k,\omega)\}$$





Observed

$$I(\omega,k)$$

(F-J Spectrogram)

Summary

- Dispersion curves of overtones are very important for Ambient Seismic Noise Tomography (ASNTM). With fundamental mode only, ASNTM is unlikely an independent and accurate structure prospecting method.
- The new method we proposed, F-J method, can help to extract the overtones' dispersion curves.
- Preliminary study shows that joint inversion of multi-modal dispersion curves can provide strong constrain on the inverted shear wave speed mode, greatly increase the accuracy of ASNTM and expend it appliability.

Thank you!

谢 谢!